INCORPORATION OF SUBSURFACE DRAINAGE AND SUBIRRIGATION INTO THE CHECKBOOK METHOD

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ABSTRACT

The highly variable climate of the Red River Valley of the North brings both flood and drought conditions, leading to an interest in subsurface water management systems (WMS). These subsurface WMS can drain excess water from the soil profile through subsurface drainage (SSD), manage water tables through controlled drainage (CD), and add additional water through subirrigation (SI). The subsurface WMS used in this study included a 21 ha CD, 17 ha CD + SI, and 16 ha undrained (control) field over a clay loam and silty clay loam soil planted with corn (2013) and soybean (2014). Both SSD and contributions from a shallow WT, through upward flux (UF), were incorporated into the Checkbook method for Irrigation Scheduling. Over the 2013 and 2014 growing seasons, daily soil moisture deficit (SMD), estimated through the modified Checkbook method ($SMD_{SSD,UF}$) produced similar, if not more accurate, estimations of daily SMD.

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LIST OF ABBREVIATIONS

CD…………………………......Control drained

CD + SI……………………..Control drained and subirrigated

CN…………………………..Curve number

ET…………………………...Evapotranspiration

ET_{ref}………………….........Reference evapotranspiration

FC…………………………...Field capacity

FD…………………………...Free drained

HYPROP……………………Hydraulic property analyzer

NDAWN……………………North Dakota Agricultural Weather Network

PAR………………………… Photosynthetically active radiation

PWP…………………………Permanent wilting point

R…………………………….Rainfall

R_{5d}…………………………..Cumulative 5 day antecedent rainfall

RRV……………………….... Red River Valley

SI…………………………....Subirrigation

SSD………………………….Subsurface drained

SMD………………………...Soil moisture deficit

SWB………………………...Soil water balance

UD…………………………..Undrained

UF…………………………...Upward flux

vwc…………………………Volumetric water content

WMP………………………..Water management practice

WSS…………………………Web soil survey

WT…………………………..Water table

θ_{FC}…………………………...Volumetric water content at field capacity (32%)

θ_{PWP}………………………….Volumetric water content at permanent wilting point (16%)

θ_s……………………………..Saturated volumetric water content (53%)

θ_r…………………………….Residual volumetric water content (9%)

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1. INTRODUCTION AND RESEARCH OBJECTIVES

1.1. Background

The Red River Valley of the North's (RRV) variable climate gives way to both flood and drought conditions providing a wide array of water management scenarios for landowners (Laird et al., 2003). Recently, a multi-decadal wet weather cycle in the RRV has led to shallow water tables (WT), where the WT is defined as the upper surface of the saturated zone (U.S. Geological Survey, 2016), and delayed planting/harvesting due to wet field conditions (Rahman et al., 2014). To reconcile these wet conditions, landowners have installed subsurface drainage (SSD) systems (tile drainage) which aim to reduce WTs by draining the soil profile to field capacity (FC) via a perforated conduit placed beneath the ground surface (Skaggs et al., 2010). Given the RRV's highly variable climate, a major benefit of these systems is their ability to be designed or retrofitted for controlled drainage (CD) and subirrigation (SI), allowing water to be retained and/or added to the soil profile. This enables land owners to not only drain during wet periods, but also retain or add water during moderate to dry periods. Management of these systems, however, can become difficult when determining the time and amount needed for SSD and SI, along with the optimal WT depth for CD and/or SI.

In the Midwest, 1-D soil water balance (SWB) models have been found to be a popular management tool when it comes to determining the time and amount needed for irrigation. These 1-D SWB models make use of a mass balance such that all water entering and leaving the system is accounted for (Jensen et al., 1990). Accurate estimation of all components in the water balance allows for calculation of the soil moisture deficit (SMD) as a residual. In particular, the Checkbook Method for Irrigation Scheduling by Lundstrom and Stegman (1988) used a mass balance to determine the daily SMD. The Checkbook method has been modified for use in several states throughout the Midwest including Michigan, Indiana, Minnesota, South Dakota, and North Dakota (Lundstrom & Stegman, 1988; Kelly, 2015; Werner, 1993; Wright, 2002). Paper and spreadsheet based forms of the Checkbook method allow the user greater flexibility with inputs such as daily ET and rainfall (Kelly, 2015). A limitation of these SWB models, however, is the lack of consideration of shallow WTs and/or SI contributions. One of the reasons behind the lack of consideration of shallow water tables is that, often times, the change in water balance due to a shallow WT is insignificant for water management purposes (Gribovszki et al., 2010). However, the introduction of subirrigation and generally high water tables of the RRV has led to the need for research towards better understanding the relationship between these high water tables and crop water consumption.

Several studies have shown that shallow water tables directly influence crop ET (Gribovszki et al., 2010). A study by Tan et al. (2002) noted corn, grown in clay loam soil, could have an average of 87 mm more ET if CD + SI is used versus a field which is allowed to drain freely (SSD). Madramootoo et al. (1993) saw that WTs maintained at 0.4 m compared to 1.0 m, in a sandy loam soil, increased soybean yields by 20%. Similarly, Mejia et al. (2000) found WTs maintained at 0.75 m, in a silt loam soil, resulted in yield increases for a soybean and corn crop of 32% and 7%, respectively, compared to a SSD plot.

This study looks at the incorporation of shallow WT contributions, either naturally occurring or induced through SI, to the Checkbook method and its effect on daily and future predictions of SMD. Improvements to daily and future predictions of SMD can add additional crop security, with the potential for increased yields, by allowing the farmer to better estimate the time and amount needed for drainage or irrigation.

1.2. Objectives

The general objective of this study was to incorporate contributions from a shallow WT, either naturally occurring or induced through SI, and removal through SSD into the mass-balance of the Checkbook method for Irrigation Scheduling in order to assist farmers in determining the time and amount needed for SSD and SI, as well as an optimal WT depth when using CD. The specific objectives were to 1) determine the relationships between shallow water tables and crop water consumption, 2) incorporate SI and SSD into a modified Checkbook method to develop a best water management practice for SSD and SI systems, and 3) develop net irrigation amounts using field measured water table, soil moisture, irrigation/drainage, and weather data.

2. LITERATURE REVIEW

2.1. Regional water problem and its history

In the RRV, shallow WTs caused by excess precipitation and poor drainage have the potential to increase soil salinity and waterlogging, and make field trafficability difficult (Guitjens et al., 1997; Skaggs et al., 2010). Recently, the negative impacts of shallow WTs have been seen in the RRV, which is in large part due to a wet weather cycle since 1993 (Jia et al., 2012). This wet weather cycle has encouraged the installation of SSD, which can help to remove excess water from the soil profile and make trafficability with heavy machinery easier during planting and harvest.

2.2. Subsurface water management practices

2.2.1. Subsurface (free) drainage

An SSD system uses perforated conduits, laid beneath the ground surface, to remove subsurface water from the surrounding soil (ASABE Standards, 2015). These SSD systems have been shown to increase yields during wet years and improve trafficability during planting and harvest. However, SSD has also been shown to have a negative impact on water quality. This can be seen through multiple studies, in which SSD increased the amount of nitrates and soluble salts in the outflow compared to surface runoff alone (Jia et al., 2012; Skaggs et al., 2010). In addition, SSD has been cited as a major contributor to the decreased water quality in the Gulf of Mexico which has resulted in algal blooms and hypoxic conditions (Skaggs et al., 2010). Hence, it is important to balance between improving crop yield and reducing the amount of nitrates and soluble salts in outflow, which can be assisted through the practice of CD (Skaggs et al., 2010).

2.2.2. Controlled drainage

A CD system uses a weir/overflow device which raises the height of the water in the drain outlet (Skaggs et al., 2010) to control the drainage outflow. Thus, CD is essentially a SSD system with the ability to control/stop drainage and adjust the water table. Some existing SSD systems can be modified into CD systems with the addition of a weir/overflow structure. By using a CD system, compared to a SSD system, a farmer or land manager can reduce subsurface drainage rates/volumes anywhere from 17-90 % (annually) (Skaggs et al., 2010). This in turn helps to reduce the amount of nitrates and soluble salts in surface waters and helps to retain crop-available water along with keeping valuable nutrients in the root zone (Drury et al., 2009). A seven year study conducted by Poole et al. (2013) showed that CD increased corn yields by 11% and soybean yields by 10% in plots with a sandy loam soil. However, even though CD systems have many benefits compared to a SSD system, it is hard to motivate land owners to modify or adjust their current SSD systems. This, in large part, is due to the fact that many land owners do not feel water quality issues are their responsibility and an increase in crop yields is not guaranteed with a CD system because a CD system does not provide drought protection nor does it act as an irrigation system during dry years.

2.2.3. Subirrigation

To counteract this problem, a combined CD and SI system can be installed, where SI is defined as the "application of irrigation water below ground surface by raising the water table to within or near the root zone" (ASABE Standards, 2005). The SI system is set up similar to that of a SSD system except with the use of a pumping station, which allows irrigation water to be pumped back into the field via the tile drainage lines. The SI water can come from either groundwater or surface water sources. By combining a CD and SI system, the landowner with an independent water source, can drain the field during wet periods and irrigate during dry periods. Along with being able to better control the soil moisture conditions in the field, a CD + SI system reduces the amount of nitrates added to surrounding surface waters and increases crop yields with proper management (Drury et al., 2009; Tan et al., 2004). A study by Tan et al. (2004) showed a CD+SI system can reduce nitrate loss by 32% and increase corn and soybean yields by 9% and 17%, respectively, in a clay loam soil. Thus, a CD + SI system essentially combines the best qualities of SSD, CD, and SI systems while eliminating or reducing the negative qualities. However, a CD + SI system requires more management and it is not yet known the amount and time needed for irrigation or drainage.

2.3. Factors influencing water management

When looking at managing a CD + SI system, an understanding of the relationship between shallow WTs, whether naturally occurring or induced through SI, and crop water consumption is important. A good understanding of this relationship requires knowledge of soils, crop specific water requirements, climatic variability, and the efficiency of the SI system (fraction of water delivered to the root zone versus the amount pumped into the field). Consideration of these site specific variables allows the irrigator to better estimate the amount and time needed for irrigation and, as a result, has the potential to increase yields and reduce costs of irrigation (Huffman et al., 2011; Steele et al., 2000).

2.3.1. Soil

An understanding of the soil characteristics is crucial for the management of any SI system. Specifically, when looking at soil characteristics, it is important to define the soil moisture content at permanent wilting point (PWP) and field capacity (FC), and determine an appropriate management allowed depletion (MAD) (Huffman et al., 2011). The PWP can be defined as the soil water content when water in the soil becomes unavailable to the plant (Coyne & Thompson, 2006). The FC can be defined as the water content of the soil once the downward movement of water (due to gravitational forces) has stopped (Coyne & Thompson, 2006). Lastly, the MAD can be defined as the decrease in soil moisture content within a predefined (manageable) range (Huffman et al., 2011). These factors help to determine how much water is available to the plants and the amount of water stress the crop may be under.

In addition, knowledge of soil texture and hydraulic conductivity is helpful for determining how water moves through the soil profile, and understanding how water is transferred, and the rate at which it is transferred, from a shallow WT to the crop. Soil texture and hydraulic conductivity affect the water holding capacity and extent of capillary rise in the soil profile (Coyne & Thompson, 2006), which in-turn affects the amount of water available to the crop. In a manual prepared for the Food and Agriculture Organization of the United Nations, Brouwer et al. (1985) noted the extent of capillary rise in sandy soils can range between 0.2 and 0.5 m, whereas in clayey soils the extent can reach up to several meters. However, even though water can contribute to soil moisture and crop ET from depths greater than 1 m in silty clay loam soils, the rate at which water travels through the soil (hydraulic conductivity) is much slower than that of sandier soils, with general conductivity estimates for a sandy loam soil at 14.11 – 42.34 micrometers per second (µm/sec) and for a silty clay soil at 0.42 – 1.41 µm/sec (NRCS, 2015). Therefore, it's important to not only look at the amount of water available within the soil profile, but also the rate at which it can be transferred to the crop. By considering soil characteristics when managing a subsurface water management system (SSD, CD, SI), a farmer can better understand how additional water will contribute to crop evapotranspiration (ET) and the overall soil moisture status of their field, as well as how water removal through SSD will influence field conditions.

2.3.2. Crop

In addition to considering various soil properties for subsurface water management, it is also important to look at varying crop water consumption of different agricultural crops. The crop water consumption can be described as the ET rate, a combination of evaporation and transpiration (Jensen et al., 1990; Senay et al., 2011). It differs on crop types and stages and the ET measurement methods. Lundstrom and Stegman (1988) provide a series of tables to estimate daily ET based on crop type, temperature, and week past emergence. In general, estimation of crop ET can be achieved through the use of both indirect (reference ET and crop coefficient, K_c) and direct ET measurement methods.

2.3.2.1. Indirect evapotranspiration estimation methods

Indirect ET estimation methods use reference ET and a crop coefficient (K_c). Reference ET (ET_{ref}) is defined as the rate of ET, not short of water, from a specified vegetative surface of uniform density and cover (Jensen et al., 1990) and the corresponding K_c curve accounts for the region specific crop growth characteristic (Jia et al., 2013). The ET_{ref} can be calculated from the Jensen-Haise (J-H) and Penman-Montieth (P-M) equations, which are both used throughout North Dakota by the North Dakota Agricultural Weather Network (NDAWN) at 66 sites (NDAWN, 2016). The P-M equation used by NDAWN is also used by the High Plains Regional Climate Center and requires daily solar radiation, dew point temperature, wind speed, and air temperature for estimation of ET_{ref}, whereas the J-H method only requires temperature and solar radiation (Irmak et al., 2008; Jia et al., 2013).

The crop specific ET (ET_c) can be calculated from the ET_{ref} and K_c (equation 2.1), where K_c represents a unique crop coefficient for each crop at different stages in a region (Huffman et al., 2011):

$$ET_c = K_c\ ET_{ref} \tag{2.1}$$

Both J-H and P-M equations used by NDAWN use alfalfa as the reference surface (Jia et al. 2013). It has been suggested that alfalfa based ET_{ref} methods provide a better estimate of ET_c for agricultural crops because alfalfa is more aerodynamically similar to other agricultural crops than grass and tends to have higher ET rates than grass (Huffman et al., 2011). In general, the ET_{ref} from an alfalfa surface is about 20-25% higher than that from a grass surface.

In North Dakota, the J-H method has been used in various water balance applications of the Checkbook method for purposes of scheduling irrigations, including paper-based form (Lundstrom & Stegman, 1988), spreadsheet-based form (Steele et al., 2010), and web-based application (Egeberg & Scherer, 1998) for several crops (corn, sugarbeets, soybean, dry beans, alfalfa, barley, wheat, potatoes). Specifically, in the paper-based form of the Checkbook method (Lundstrom & Stegman, 1988), daily ET_c was determined through the J-H reference ET method, with known maximum temperature and days past emergence in a table format. The same crop ET_c tables were also included in the spreadsheet-based form of the Checkbook method (Steele et al., 2010). A web-based utilization of the J-H method, through the NDAWN Crop Water Use application (Egeberg & Scherer, 1998), provides daily ET_c estimates for ten crops in North Dakota (alfalfa, barley, corn, dry bean, potato, soybean, sugarbeet, sunflower, turf grass, and wheat) by estimating ET_{ref} with the J-H method (Jensen & Haise, 1963) and using K_c curves developed by Stegman et al. (1977).

2.3.2.2. Direct evapotranspiration estimation methods

Even though indirect methods for estimation of crop ET_c (J-H and P-M) have been commonly used for water-balance/irrigation scheduling purposes (Kincaid & Heermann, 1974; NDAWN, 2015), they fail to take into account site-specific influences to the water balance, such as a shallow WT, SSD, SI, and (or) isolated rainfall events, each of which has the potential to influence ET_c. Direct estimation of ET_c through an Eddy Covariance (EC) system or soil water balance (SWB) approaches, can help to incorporate some of the site specific contributions/removals from the water-balance.

The use of an EC system for estimation of ET_c has been considered as one of the standards for ET estimation, with its accuracy/precision shown in multiple studies (Farahani et al., 2007; Scott, 2010). The EC system, also known as Eddy Correlation and Eddy Flux (Campbell Scientific, 2013), determines ET_c by measuring the turbulent fluxes of heat and vapor above the ground surface (Campbell Scientific, 2013; Sumner et al., 2001) and uses complex mathematical equations to evaluate the data. When looking at the energy balance (i.e. energy budget for plant canopy), the EC system measures the latent and sensible heat fluxes (Sumner et al., 2001), while net radiation and soil heat flux are measured independently. The latent heat flux can be described as the energy removed during the liquid to vapor phase, whereas sensible heat describes the energy removed from the canopy due to temperature changes across the canopy and atmosphere (Sumner et al., 2001). Both latent and sensible heat fluxes move through the air by turbulent eddies. Thus, when measuring these energy components, the speed of measurement and the quality must be high, at about 20 Hertz (Hz).

Another popular, and much simpler, method for direct estimation of ET_c is the SWB method, also known as soil water budget. This method uses a mass balance approach to estimate

ET_c (Senay et al., 2011). In North Dakota, the SWB method was used with the J-H ET_{ref} method (Jensen & Haise, 1963) to develop K_c values for various crops. Advantages of the SWB method include the ability to estimate site specific ET_c at a much lower cost and complexity, as compared to the EC method. However, use of the SWB method involves assumptions of homogenous soil layers, vegetation, and water table depths. There is also difficulty in measuring the amount of water lost to deep percolation (DP). In a one year study, by Wilson et al. (2001), a positive correlation was found between ET_c estimated from SWB and EC, however the data was highly variable. They concluded that groundwater contributed to this variability, emphasizing some of the limitations associated with the SWB method and its lack of consideration for subsurface contributions through upward flux of a shallow WT and (or) removal from DP.

To compensate for the relative complexity and expense of an EC system and reduce the need for estimation of each component of the water balance through the SWB method, an alternative method for ET_c estimation, involving the use of photosynthetically active radiation (PAR) data, has been proposed by Migliaccio et al. (2012). PAR covers the radiation band between 400 and 700 nm [0-2500 μmol/(m^2sec), visible light] and plays a crucial role in the development of plant matter (Al-Shooshan, 1997). Of the solar radiation that comprises the PAR band, 85% is absorbed by the plant and as a result, it has been hypothesized that PAR may provide a direct relation to ET (Al-Shooshan, 1997). In addition, Samani (2000) noted at least 80% of ET_{ref} can be attributed to temperature and solar radiation. Migliaccio et al. (2012) found the incorporation of PAR, air temperature, and volumetric soil moisture into a linear regression model (calibrated with EC data) was able to closely estimate EC estimated ET_c (EC-ET).

Kolars et al. (2013) compared EC, SWB, and PAR methods for their ability to accurately estimate ET_c and, in turn, the soil moisture content of the field for irrigation purposes. Results indicated that the SWB method was highly variable showing little to no correlation with EC estimated ET_c. However, the PAR method, after calibration with EC data, visually showed a close relationship with EC estimated ET_c with an R^2 of 0.94 and RMSE of 0.02 mm/30 min, indicating that this method for ET_c prediction may have further potential with additional research in differing climates, crops, and soils (Kolars et al., 2013). Overall, ET plays an important role in the soil water balance and accurate estimation is critical for irrigation scheduling purposes.

2.3.3. Climatic variability

Another factor which may make management of a SSD, CD, or SI field difficult, is dealing with the high climatic variability that exists in the RRV. Effective irrigation scheduling requires knowledge of soils and seasonal variations in crop water consumption, as well as an understanding of the climatic variability. The RRV has a highly variable climate requiring a highly adaptable irrigation/drainage management tool/method. Part of this climatic variability comes in the form of rainfall amounts, which can lead to flood and (or) drought conditions (Laird et al., 2003). In order to use soil water balance methods for irrigation/drainage scheduling in the RRV, a management tool must be able to adapt to both dry and wet extremes (waterlogged conditions and (or) drought).

In addition to the incorporation of rainfall, average wind velocity also plays a role in the soil water balance as seen through its use in estimating ET through the EC system (Campbell Scientific, 2013). On relatively windy days, it has been noted that ET can increase compared to days with relatively low to no wind (Viessman & Lewis, 2003). This increase may be due to the fact that when wind is present the mass of air above the crop is moving, as this mass of air is moved further away from the crop there is a potential for new, less saturated, masses of air to move in with the ability to hold more water from ET. Thus, it is important to also consider the impact of wind velocity on ET estimates for a SWB.

2.3.4. Subirrigation efficiency

The efficiency of an irrigation system is important for understanding the amount and time needed for irrigation and represents the fraction of water delivered to the root zone versus the amount pumped into the field. Different efficiencies have been developed for various surface irrigation systems such as the intermittent mechanical-move (70-80%), continuous mechanical-mover (80%), and solid-set and permanent (70-80%) sprinkler irrigation systems (Huffman et al., 2011; Fangmeier & Biggs, 1986). Specifically, irrigation efficiencies of 80-85% for a center pivot system were used in conjunction with Lundstrom and Stegman's (1988) Checkbook method. Efficiencies for microirrigation systems (trickle, drip, or subsurface drip irrigation systems) range from 80-90% due to the direct application to the root zone which helps to eliminate losses from evaporation (Huffman et al., 2011; Fangmeier & Biggs, 1986). However, more research is needed to better understand the efficiency of subirrigation systems. One method for determining this subirrigation efficiency stems from the use of a soil water balance algorithm. Given that each part of the soil water balance algorithm can be measured through various instruments located in the field, it is possible to back solve for the net irrigation.

2.4. Water balance over cropland

All of the irrigation management factors (soils, crop, climate variability, and irrigation efficiency) must be considered when using a soil water balance method to schedule irrigations. Accurate estimation of the different parameters in a soil water balance is crucial when trying to estimate a missing component of this water balance. For example, when trying to estimate the change in soil moisture of a system, it is important to accurately and precisely measure all inflow (rainfall, irrigation, etc.) and outflow (ET, drainage, surface runoff, etc.) from the system as

$$\text{Change in soil moisture} = \text{Inflow} - \text{Outflow} \tag{2.2}$$

In the RRV, variations of the soil water balance method have been used to help schedule irrigations for the purposes of maintaining or increasing yields, and reducing water costs/requirements for irrigation (Steele et al., 2000). However, even though SWB methods have been shown to be effective for monitoring the soil moisture status of a field, it is hard to estimate subsurface water contributions, either through a naturally occurring high WT or induced through SI. These two components, net daily irrigation through SI and shallow WTs, are critical parts of the soil water balance equation.

2.4.1. Shallow water table contributions

Consideration of a shallow WT, either naturally occurring or induced through SI, is rarely taken into account when using SWB methods in the RRV. However, the impact of a shallow WT on crop ET and yield can be significant. Madramootoo et al. (1993) saw that WTs maintained at 0.4 m compared to 1.0 m, in a sandy loam soil, increased soybean yields by 20%. Similarly, Mejia et al. (2000) found WTs maintained at 0.5 and 0.75 m, in a silt loam soil, resulted in yield increases of 37% (0.5 m) and 32% (0.75 m) for a soybean crop and yield increases of 7% (0.5 m) and 7% (0.75 m) for a corn crop, compared to a freely drained plot.

2.4.2. Ground water flow

Various factors affect the flow and transport of soil water through the partially saturated (or unsaturated) zone of a soil profile. The partially saturated or unsaturated zone can be described as the portion of the soil profile where the matric potential of the soil water is negative or the soil water content is less than the FC of the soil (Nielsen et al., 1986). In this zone, both liquid and gasous phases of soil water exist (Coyne & Thompson, 2006). Flow of soil water in the unsaturated zone is affected by a multitude of factors including various physical and chemical factors (Nielsen et al., 1986). The physical processes affecting soil water flow include hydrological aspects such as ET, infiltration, percolation, and soil moisture content (Nielsen et al., 1986). Dominating chemical factors influencing soil water include, but are not limited to, presence of soluble salts (saline soils) and electrochemical characteristics of clay-water systems (Tindall & Kunkel, 1999). These chemical factors have the potential to affect stability of soil aggregates during wetting through processes of swelling, slaking, or dispersion, which in turn affect the flow of soil water through the soil profile (Tindall & Kunkel, 1999).

Even though many physical and chemical parameters play a dominant role in the flow of soil water through the unsaturated zone, the relationship between soil water potential, hydraulic conductivity, and soil moisture content for a particular soil is critical to understanding flow in the unsaturated zone (Nielsen et al., 1986). These parameters not only help to describe the availability of soil water for root uptake (transpiration), but also help to estimate the movement, or rate of flow, of soil water through a partially saturated zone (Ragab & Amer, 1986).

By understanding both physical and chemical properties of the soil and how they influence water movement, it is possible to estimate the amount of water contributing to crop ET through upward flux (capillary water) (Yang et al., 2007). This can be seen through an empirical equation developed by Yang et al. (2007) where inputs include daily ET, depth to WT, and soil moisture, as well as certain soil characteristics such as the saturated and residual water contents. Once contributions from a shallow WT through upward flux (UF) are estimated, they can be incorporated into a SWB and used in the Checkbook method for determination of the soil moisture status.

2.5. Checkbook method

As described earlier, the Checkbook method for Irrigation Scheduling uses a soil water balance algorithm to help determine the soil moisture status of the field and when to irrigate. The Checkbook method's accuracy and reliability can be seen through a series of studies conducted in Oakes, ND (Steele et al., 2000; Steele et al., 1997). In particular, a study conducted by Steele et al. (1997) used a similar SWB method as the Checkbook method to determine the soil moisture status of a field plot. In this study, it was found that monthly adjustments to the predicted soil moisture estimates provided relatively accurate results, with the accuracy increasing with the increased frequency of adjustment to in field soil moisture measurements (Steele et al., 1997). In addition, the reliability of the method for determining times of best irrigation can be seen through a study conducted by Steele (2000), where four methods for irrigation scheduling were compared, in which two methods dealt with soil water balance similar to the Checkbook method. Through this study, it was found that the two methods, which were most similar to the Checkbook method, were favorable not only for the increase in yield and significant water savings of about 30%, but also for the relative ease of use and familiarity with local landowners/farmers (Steele et al., 2000).

2.6. Scope and objectives

The Checkbook method for irrigation scheduling is a popular and relatively simple method used in the upper Midwest to help with irrigation management decisions. However, the Checkbook method is meant for use with an above ground sprinkler irrigation system and does not consider drainage outflow through a SSD system. Thus, the incorporation of SSD, CD, and (or) CD + SI in the Checkbook method would be helpful when it comes to determining the time and amount needed for irrigation and (or) drainage to keep the SMD within the MAD. Essentially, the introduction of SI and SSD in the soil water balance algorithm will allow the landowner to better manage the soil moisture deficit so that the field remains at optimal moisture conditions. In the end, the results of this study will allow a better understanding on the effects of a shallow water table on crop water consumption and, as a result, assist in the development of better management plans using the modified Checkbook method for a CD + SI system. Benefits of a better management plan for a CD + SI system should consist of increased yields, improved water quality, and reduced pumping costs.

This paper will focus on subsurface drainage and subirrigation water management by modifying the Checkbook irrigation method. The specific objectives of the study are to:

1) Determine the relationships between shallow water tables and crop water consumption.
2) Incorporate SI and SSD into the modified Checkbook method to develop a best water management practice for SSD and SI systems.
3) Develop net irrigation amount using field measured water table, soil moisture, irrigation/drainage, and weather data.

3. MATERIALS AND METHODS

3.1. Study site

The study site (46º59’20’’N and 96º41’06’’W) is in the Buffalo River watershed of Clay County, MN (Figure 3.1). The Buffalo River watershed is primarily agricultural with 66% of the watershed classified as cropland, 9% forest, 9% grassland, 7% wetland, 5% residential, and 4% open water (NRCS, 2007). The study area tends to have mild summers (average temperature 19.3 ºC) and cold winters (average temperature - 8.5 ºC), with average annual precipitation and potential evapotranspiration ranging between 533 – 635 and 1103-1478 mm/year, respectively (NDAWN, 2015; NRCS, 2007).

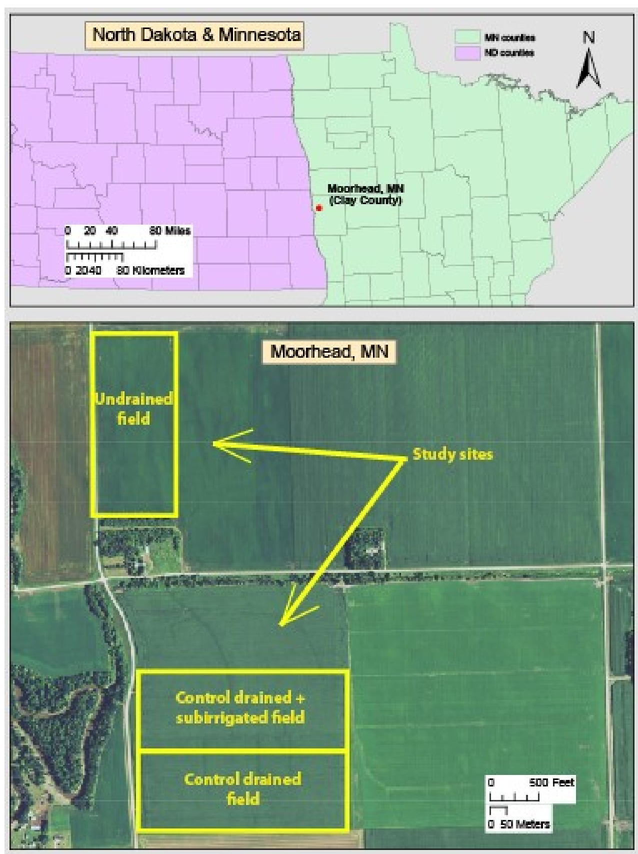


Figure 3.1. Study site location as well as the locations of the differing water management practices such as the undrained, control drained, and control drained + subirrigated fields.

The study site consists of three different water management practices (WMP): a 16 hectare (ha) undrained (UD), 21 ha CD, and 17 ha CD + SI field, each under a corn/soybean/sugarbeet crop rotation (Figure 3.2 and Table 3.1).

Table 3.1. Three Water Management Practices and their crop rotation 2011-2014.

Water Management Practice	**Area (ha)**	**Year**	**Crop**
Undrained	16	2011	soybean
		2012	corn
		2013	soybean
		2014	corn
Control drained	21	2011	sugarbeet
		2012	corn
		2013	corn
		2014	soybean
Control drained and Subirrigated	17	2011	sugarbeet
		2012	corn
		2013	corn
		2014	soybean

The UD field (control plot) does not have a subsurface drainage or irrigation system. The CD field drains by gravity through the non-pressurized perforated conduit laid beneath the ground and a control structure, placed at the outlet, to control drainage and manage the WT. The SI field has the same functionality as the CD field, except with the ability to add water directly to the soil profile through the subsurface tile lines.

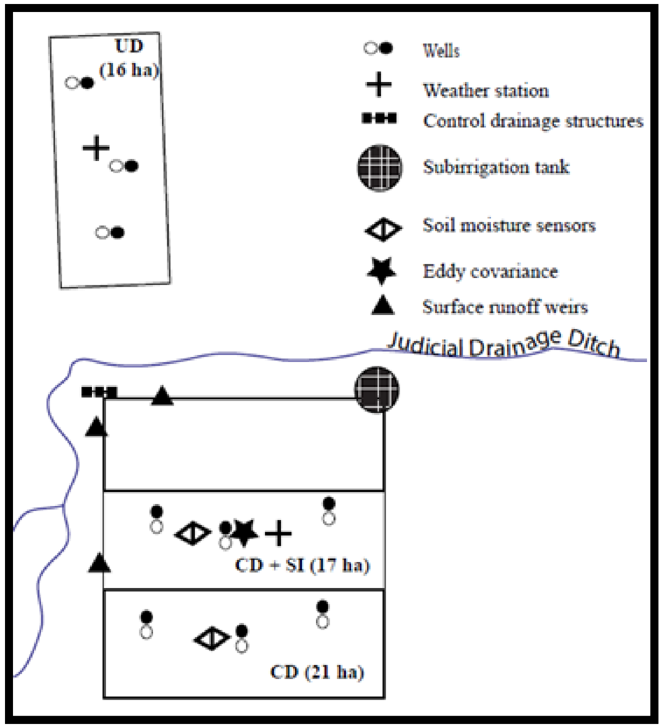


Figure 3.2. Study site schematic with three water management practices, undrained (UD), control drained (CD), and CD + subirrigated (SI); and their respective locations and size.

3.2. Soils

All three plots have similar soils with the predominant soils being Bearden silt loam (fine-silty, mixed, superactive, frigid Aeric Calciaquolls) and Colvin silty clay loam (fine-silty, mixed, superactive, frigid typic Calciaquolls), both poorly drained (NRCS, 2013). In-field soil analysis determined the top meter of the soil profile was 0-3% sand, 55-70% silt, 30-45% clay and the bottom meter of the soil profile was 0-3% sand, 55-75% silt, 25-45% clay, respectively (Jia, X., 2012). Further description on the soil analysis is provided in the Sustainable Agriculture Research and Education 2012 annual report by Jia, X.(2012).

3.3. Subsurface water management system

The subsurface water management system for CD and CD + SI fields consists of a pattern tile design with 7.63 cm diameter laterals at 12.2 m spacing, lying roughly 1 m below the ground surface. Laterals run east to west at a 0.1% grade resulting in a 0.6 m drop. Each water management system (CD, CD + SI) has its own drainage main, running along the western border of the field, and its own irrigation main, running along the eastern border of the field (Figure 3.3). The separate drainage and irrigation mains allow water to be managed individually for each section of the field and to run along the slope.

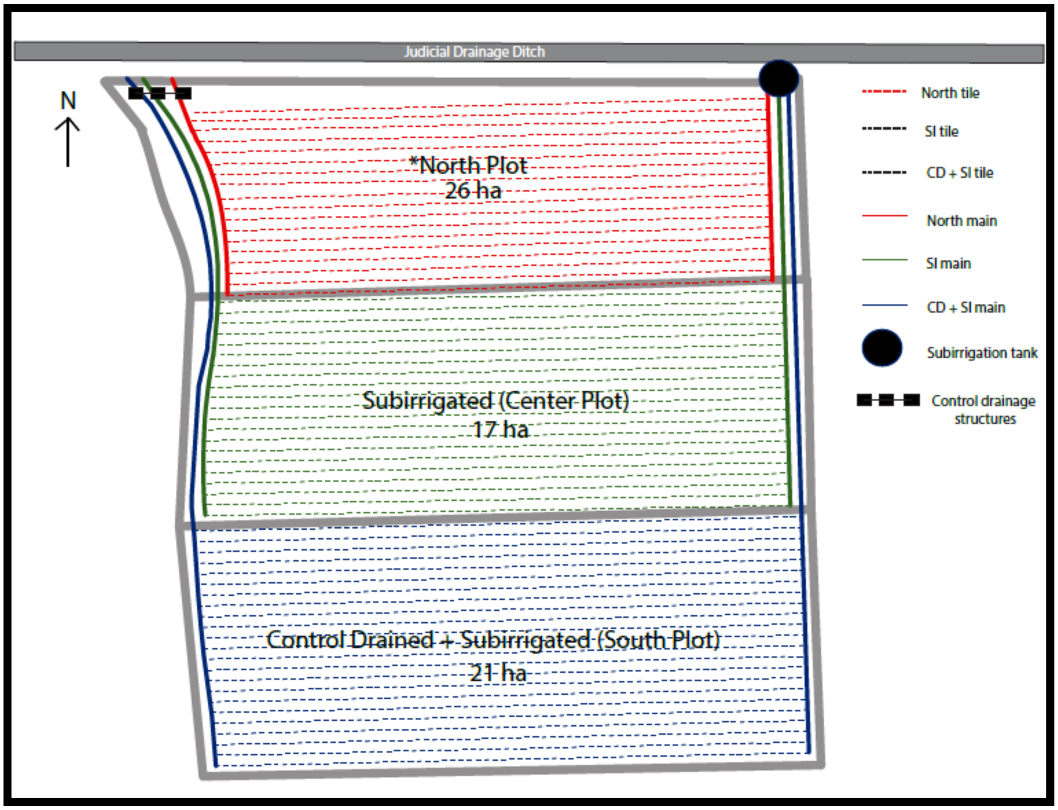


Figure 3.3. Subsurface water management system layout for control drained (CD) and CD + subirrigated (SI) fields. *North Plot was not included in the research project given it was bordered by a judicial drainage ditch on the north edge.

In addition, control structures were placed at both CD and CD + SI drainage outlets to manage WTs and control drainage (Figure 3.4).

Figure 3.4. Three control drainage structures used to manage the water table for three sections of the study site as noted in figure 3.3.

The control structures consist of a rectangular column with flashboards to adjust/control water levels in-field. If water levels exceed the height of the flashboard within the control structure, then water overtops the flashboard and drains freely. The flashboards can also be raised to mimic a free-drainage scenario, by allowing water to drain freely from the tile without having to overtop a flashboard. A detailed description of how daily drainage and irrigation was estimated is provided in the "Methods" section.

3.4. Instrumentation

3.4.1. Water table depth

Each WMP (UD, CD, CD + SI) had 6 piezometers (screened wells) such that pairs were randomly placed in the upper, middle, and lower portions of each plot at 1 and 6 m from the tile line (Figure 3.2), resulting in a total of 18 wells over the three WMPs. Each well extends to a depth of 2 m and contains a barometric pressure compensated transducer which continuously records the WT elevation at one hour intervals. Barometric data was collected from a nearby North Dakota Agricultural Weather Network (NDAWN) weather station in Fargo, ND

(NDAWN,2015). Manual WT measurements were taken monthly to ensure proper function of equipment.

3.4.2. Soil moisture sensors

Soil moisture was continuously monitored with a Stevens Hydra Probe II, coaxial impedance dielectric sensor, both near and between tile lines at 5, 15, 30, 45, 60, 75, and 90 cm depths in the middle of both CD and CD + SI plots. In addition, soil cores were collected up to a 1.2 m depth at each well location (as previously described in the 'Water table depth' section). Each soil core was subdivided into five 24 cm sections, starting from the ground surface and working down. A soil sample was taken from each 24 cm section and hydraulic properties determined through the use of a HYdraulic PROPerty analyser (HYPROP). The HYPROP instrument continuously monitors the tension, at two depths, and weight of the soil sample from saturation to air dry (UMS, 2015). By continuously monitoring the weight and tension of the soil sample, it is possible to estimate certain hydraulic properties through an evaporation method proposed by Wind (1968) and Schindler (1980), such as the volumetric water content at FC (θ_{FC}, 1/3 bar), PWP (θ_{PWP}, 15 bar), residual water content (θ_r), and saturated water content (θ_s) (UMS, 2015). Estimates of θ_{FC}, θ_{PWP}, θ_r, and θ_s were first determined for each soil sample, then averaged over each soil core, and finally averaged over each water management practice (CD, CD + SI, UD) (Table 3.2). When comparing HYPROP results with those reported by Web Soil Survey (WSS), HYPROP estimates fell within or near the range of acceptable values provided by the Natural Resources Conservation Service (NRCS) through WSS (Table 3.2).

Table 3.2. Volumetric soil water content at field capacity (1/3 bar), permanent wilting point (15 bar), saturated water content, and residual water content as determined through HYPROP experiment for undrained, control drained, and control drained + subirrigated sites. Web Soil Survey soil analysis of field capacity and permanent wilting point is provided to validate HYPROP findings.

Volumetric soil water content listed in percent (%)						
	HYPROP Analysis				Web Soil Survey Analysis	
Water management practice	Field capacity (1/3 bar)	Permanent wilting point (15 bar)	Saturated water content	Residual water content	Field capacity (1/3 bar)	Permanent wilting point (15 bar)
Control drained + subirrigated	32.1	17.0	53.4	8.7	30.1 - 32.3	15.5 - 18.9
Control drained	30.4	15.5	52.6	7.4	30.1 - 32.4	15.5 - 18.1
Undrained	35.5	21.0	52.2	11.4	31.7 - 34.0	18.0 - 28.5

In addition to verifying soil hydraulic properties with the HYPROP instrument, Hydra probe II sensors continuously monitored volumetric soil moisture. To ensure proper function of the Hydra probe II sensors, a range of feasible values were determined through use of HYPROP estimates of θ_r (9.2% volumetric water content, vwc) and θ_s (53.0% vwc), such that maximum and minimum recorded soil moisture estimates were checked to lie within this range (9.2 – 53.0% vwc). In addition, 3-4 points were used for calibration of each soil moisture sensor (depending on data availability). Calibration dates corresponded to days in which a significant rainfall event (accumulative rainfall event larger than 10 mm) had occurred. Accumulative rainfall amount is the daily total rainfall minus the surface runoff estimated through the Soil Conservation Service (SCS) curve number method (described in the ‘Methods’ section). Soil moisture values lying above field capacity (θ_{FC}, 32% volumetric water content) were calibrated to θ_{FC}, while those lying below θ_{FC} were left as is and not considered in calibration. It was assumed three days after a significant rainfall event (rain event greater than 10 mm), soil moisture between the 15 and 90 cm depth would have returned to θ_{FC} if not lower (Brouwer et al., 1985; Wright, 2002). For the top 5 cm of the soil profile, the soil moisture was assumed to be at or below θ_{FC} within one day of a significant rain event. Hence, if a soil moisture reading was above θ_{FC} at one of the predefined points, it was assumed the sensor needed adjustment. If a soil moisture reading was below θ_{FC} at one of the three predefined points, then no adjustment was needed given the sensor provided a reasonable soil moisture value. Once the three or four points were selected, linear regression was used, with an intercept set at (0, 0), to determine the adjustment factor for each sensor. Table 3.3 lists the dates used for calibration along with information concerning the significant rain event.

Table 3.3. Soil moisture sensor calibration dates for control drained and control drained + subirrigated field sites.

Volumetric soil moisture calibration dates						
Year	Date of rain event	Rainfall (mm)	Date of calibration for sensors at 5 cm depth	Calibration value (%)	Date of calibration for sensors at and below 15 cm	Calibration value (%)
2013	6/9	11.2	6/10	32.0	6/12	32.0
	6/23	25.5	6/24	32.0	-	-
	6/26	10.0	6/27	32.0	6/29	32.0
	7/11	10.4	7/12	32.0	7/14	32.0
2014	5/12	13.0	5/13	32.0	5/15	32.0
	6/5	16.4	6/6	32.0	6/8	32.0
	6/15	25.8	6/16	32.0	6/18	32.0
	-	-	-	-	*6/20	*53.0
	7/6	10.4	-	-	7/9	32.0
	9/4	29.2	9/5	32.0	9/7	32.0

*Calibration date and value for a single Hydra probe soil moisture sensor which was known to be submerged beneath the water table, resulting in the saturated volumetric water content being used for calibration.

3.4.3. Wireless weather stations

Two wireless weather stations (Onset Corporation, HOBO weather station) were deployed near the center of the UD and CD + SI sites. An additional weather station was placed 1.6 km east of the UD weather station on cropland with a similar crop and soil as that of the UD site. These stations included instruments which collected Photosynthetically Active Radiation (PAR), daily rainfall, air temperature, relative humidity, soil temperature and soil moisture data. A standard tipping bucket rain gage, conforming to National Weather Service recommendations for a 20.32 cm funnel orifice, was also set up near the SI weather station. Rainfall data from the three weather stations was used to verify daily rain estimates provided by the standard tipping bucket rain gage, and also served to fill in gaps when there was missing data. PAR estimates from the CD + SI weather station were used in 2013, and PAR estimates from the weather station located 1.6 km east of the UD station, were used in 2014 due to unreasonably low PAR values at the CD + SI station. The low PAR values at the CD + SI site may have been caused by a buildup of soil/organic matter on the sensor head. Provided the PAR sensor measures the number of photons between 400-700 nanometers in wavelength, it is assumed that PAR estimates would not have varied significantly within a one 1.6 km radius, and given all three wireless weather stations are located within 1.6 km, PAR readings at one station should be relatively similar, if not the same, to the others.

3.5. Methods

3.5.1. Drainage

Drainage amounts were estimated through either a 60-degree V-notch weir, 16.2 cm in height, or a rectangular weir, 31.4 cm in length, located within the control drainage structure (Figure 3.5a and 3.5c). When drainage exceeded the amount which could be measured by the V-notch weir (i.e. water overtopped the weir), the cross section of the weir changed shape to that which included the edges of the control structure as shown in Figure 3.5b. There were three flow/drainage scenarios which required three different weir equations to estimate the flow (Figure 3.5).

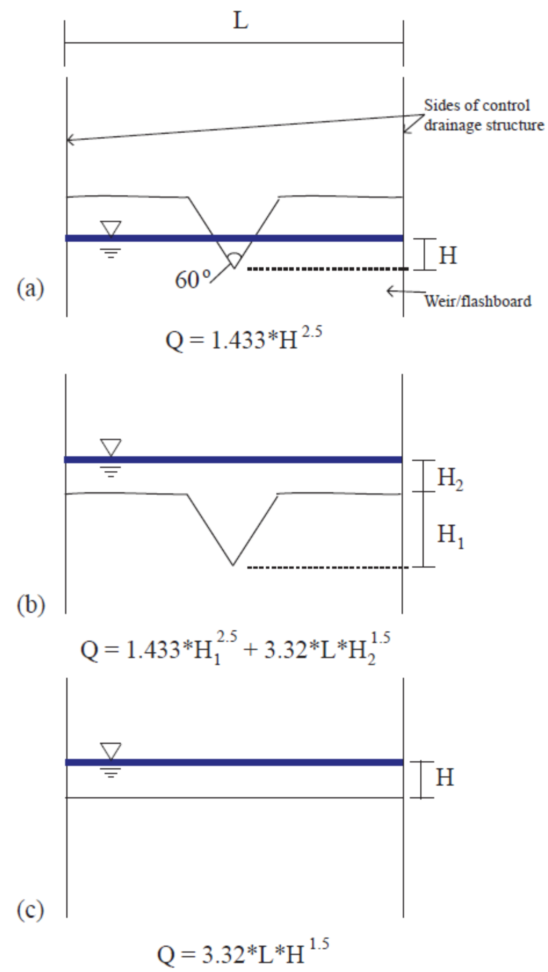


Figure 3.5. Three different drainage conditions, within the controlled drainage structures, which require three weir equations for estimating drainage amount (Q, m^3/s). For the condition in (a) water flows through a V-notch weir, (b) water flows above a V-notch weir and horizontal edge, and in (c) water flows over a horizontal edge baffle only. In the figure H represents the water level above the weir (m) and L is the width of the weir between two sides of the controlled drainage structure (0.314 m).

3.5.2. Irrigation

A variable frequency drive pump was used to transfer water from an adjacent judicial ditch to a holding tank (4.26 m tall x 2.98 m diameter) located in the northeastern corner of the study site (Figures 3.2 and 3.6). The volume of water leaving the tank, for irrigation, was recorded before entering a manifold, which then routed the water to several different fields.

Flow volumes at the inlet of the manifold and along the main for the CD + SI field were recorded through use of an inline turbine flow meter. Multiple in-field readings of these flow meters were used to estimate daily water use and SI amounts. Taking the volume of flow which had been delivered and dividing by the time between meter readings yields the estimated flow rate (L/min) (Table 3.4). These daily values were then converted to a depth equivalent over the CD + SI field (17 ha).

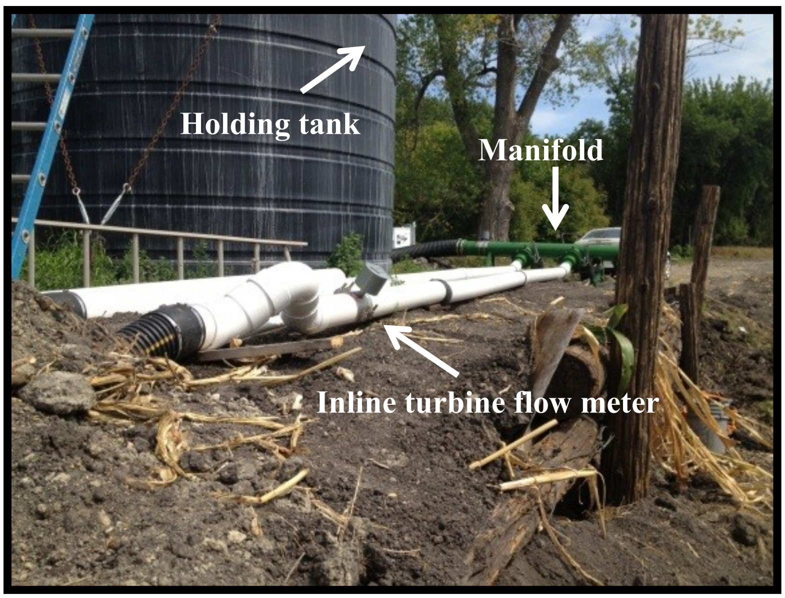


Figure 3.6. Holding tank used to store and deliver irrigation water, under gravity, to different field sites. Once water was routed through a manifold, an inline turbine flow meter was used to record flow volumes delivered specifically to the subirrigated study plot.

To check whether the pumping rate between meter readings was constant, a current sensor, which recorded variations in electrical current at a 10 minute time interval, was installed. The current reflects the pumping rate for a specific pump (pump curve) and therefore signifies a change in flow rate or delivery of irrigation water to the various field plots. A constant current indicates a relatively constant flow rate, whereas an increase/decrease in current indicates an increase/decrease in flow rate. Figure 3.7 shows the trend in electric current over the irrigation period for 2014.

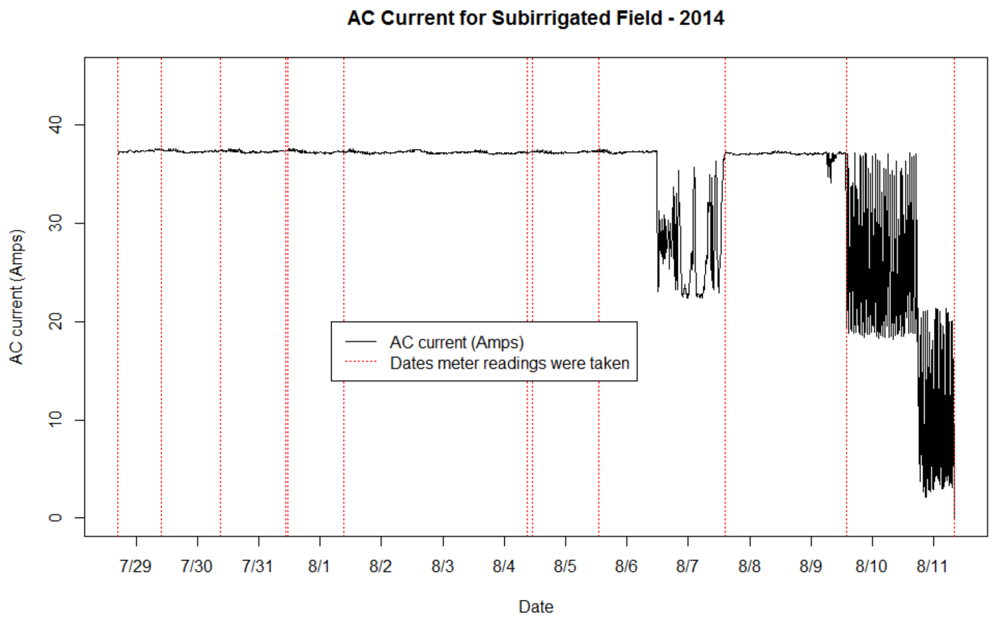


Figure 3.7. Electric current during subirrigation event, 7/28 – 8/11/2014.

When the current remained relatively constant between meter readings, it was assumed that flow rates were also constant. Out of the meter readings taken (Table 3.4), the only time periods which experienced a significant shift in current were between 8/5 – 8/7 and 8/9 - 8/11, in which case the time interval was sufficiently small, daily differences in SI amounts were considered negligible.

Table 3.4. Dates and values of meter readings for the control drained + subirrigated study site over the 2014 growing season.

Field meter readings for water delivered to the control drained + subirrigated site		
Date and Time	Meter Reading (x100 liters)	Notes
7/28/14 5:00 PM	7,332	Begin irrigation
7/29/14 10:00 AM	13,548	
7/30/14 9:00 AM	22,251	
7/31/14 10:30 AM	31,233	
7/31/14 1:15 PM	32,191	
8/1/14 9:00 AM	41,552	
8/4/14 9:00 AM	62,459	
8/4/14 11:00 AM	63,266	
8/5/14 12:45 PM	70,976	End irrigation
8/7/14 2:30 PM	70,976	Begin irrigation
8/9/14 2:00 PM	86,307	
8/11/14 8:00 AM	92,213	End irrigation

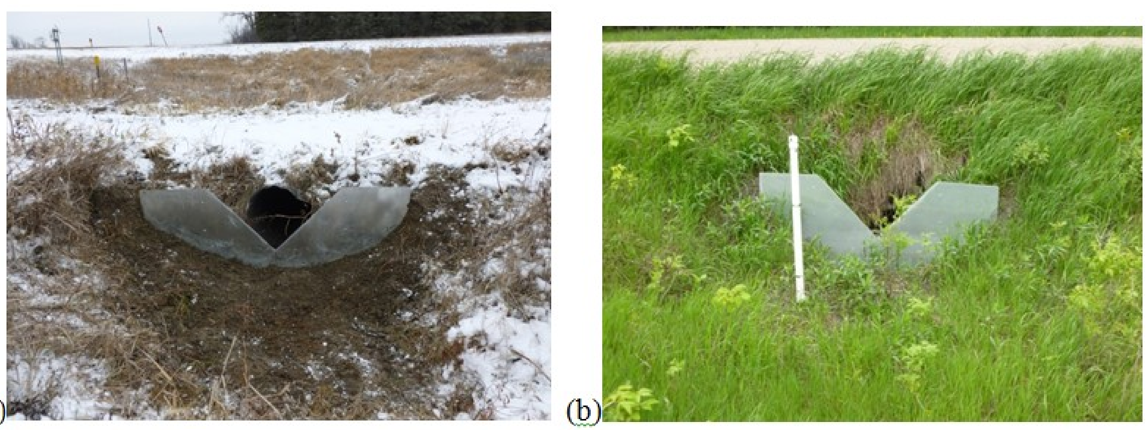
In 2013, due to large gaps in data collection, the total amount of SI water delivered could not be directly estimated by using the previously described method. Instead, periodic recordings of water delivered to the CD + SI portion of the field were used to provide an average for the amount of water delivered during the time SI took place (189-284 L/min). At this pumping rate, 189-284 L/min, over the time of SI (7/30/2013 – 8/11/2013), would have resulted in less than a 12.7 mm equivalent rainfall event. Hence, for 2013, daily irrigation amounts were simply the total amount of irrigation water delivered over 7/30/2013 – 8/11/2013 divided by the number of days SI took place (16 days), which resulted in a 0.79 mm/day irrigation rate.

3.5.3. Surface runoff

Surface runoff was estimated using the SCS curve number method provided in Huffman et al. (2011), with consideration of antecedent moisture conditions. It was determined that for agricultural lands with straight row crops, a hydrologic soil group classification of D (highest runoff potential, with mostly clayey soil with a high swelling percent), and an average runoff condition, the curve number (CN) is 90. In addition, antecedent moisture conditions were taken into account which either increased/decreased the CN depending on the five day antecedent rainfall (R_{5d}). Adjustments to CN, dependent on antecedent moisture conditions, were estimated as

$$\mathrm{CN}=\begin{cases}0.87\ \mathrm{CN}, & R_{5d}<36\\ \mathrm{CN}, & 36\leq R_{5d}\leq 53\\ 1.07\ \mathrm{CN}, & R_{5d}>53\end{cases} \tag{3.1}$$

where CN is 90 and R_{5d} is the five day antecedent rainfall total in mm. Surface runoff dates were validated with water level sensors placed near three culverts surrounding the CD and CD + SI fields (Figures 3.2 and 3.8). A water level sensor was placed inside perforated tubing which was then placed in front of a weir and culvert (Figure 3.8b). The locations of these weirs are shown in Figure 3.2. Exact estimation of flow passing over the weirs was not considered for this study as delineation of the contributing area was difficult due to relatively flat topography. In other words, if flow estimates were calculated, it is unknown how much area actually contributed to the runoff and therefore makes it difficult to estimate depth equivalents.



(a) (b)

Figure 3.8. V-notch weirs placed in front of culverts which drain the control drained and control drained + subirrigated portions of the study site, (a) is located in the northwest corner of the study site and (b) is located midway along the western edge of the control drained + subirrigated site as noted in figure 3.2.

3.5.4. Evapotranspiration

For this study, ET data estimated through EC was considered the standard and data was processed following methods described in Rijal et al. (2012). An additional method was also used to estimate ET, for those sites without an EC system, and involved the use of PAR. Use of PAR has been considered as an alternative to measure ET (Al-Shooshan, 1997; Migliaccio et al., 2012). PAR covers the band between 400 and 700 nm and plays a crucial role in the development of plant matter (Al-Shooshan, 1997). When solar radiation lies within the PAR band, green leaf absorption of PAR can reach 85% and as a result it has been hypothesized that PAR may provide a direct relation to ET (Al-Shooshan, 1997). Two undergraduate students, participating in a National Science Foundation Research Experience for Undergraduates program at the University of Florida, used three field estimated variables (air temperature, volumetric soil moisture, and PAR) and multiple linear regression to estimate ET measured by EC and had favorable results with coefficients of determination (R^2) close to 1.0 (Migliaccio et al., 2012).

For this study, linear regression was used to relate EC- ET and PAR, at the SI site, over a small time interval (6/20 – 8/2) during the growing season when the crop was well established and soil moisture levels were well above the PWP (θ_{PWP} =16% vwc). Additional variables were considered for multiple linear regression such that EC-ET could be written as a function of PAR, air temperature, volumetric soil moisture, and wind speed, but the inclusion of additional variables (air temperature, volumetric soil moisture, and wind speed) did not produce a model with a higher correlation (R) compared to the simple linear regression with a single variable (PAR). The resulting linear regression equations can be written as

$$ET_{corn}=0.0009186\ PAR+0.0024309 \tag{3.2}$$

$$ET_{soybean}=0.0009234\ PAR+0.0022148 \tag{3.3}$$

where ET_{corn} is the evapotranspiration estimate for corn in mm/30 min, $ET_{soybean}$ is the evapotranspiration estimate for soybean in mm/30 min, and PAR is the instantaneous photosynthetically active radiation in W/m^2 recorded every 30 minutes. An ET prediction model based solely on PAR, fails to take into account the current moisture status of the crop and therefore tends to over predict ET when the soil moisture content is below FC (θ_{FC} = 32% vwc). To account for soil moisture effects on ET, a modification was made to the linear regression model which involved reducing the value of PAR based on soil moisture such that if soil moisture fell below θ_{FC}, then the value of PAR would be reduced. Adjustments made to PAR, based on soil moisture, were calculated as

$$PAR_{Adj} = \begin{cases} PAR, & \theta_{30} \geq \theta_{FC} \\ \left(\frac{\theta_{30}}{\theta FC}\right) PAR, & \theta_{30} < \theta_{FC} \end{cases} \tag{3.4}$$

where PAR is instantaneous photosynthetically active radiation in W/m^2 recorded at 30 minute intervals, θ_{30} is the volumetric soil water content averaged over a 30 cm depth at 30 minute intervals, and θ_{FC} is the volumetric water content at field capacity (32%). Through substitution of PAR_{Adj} into equations 3.2 and 3.3, ET measurements for corn or soybean can be estimated from

$$ET_{corn} = 0.0009186\ PAR_{Adj} + 0.0024309 \tag{3.5}$$

$$ET_{soybean} = 0.0009234\ PAR_{Adj} + 0.0022148 \tag{3.6}$$

Equations 3.5 and 3.6 were used to estimate ET over the different water management practices (CD, CD + SI) for both corn (ET_{corn}) and soybean ($ET_{soybean}$) crops, given soils were similar and PAR and soil moisture data (up to a 30 cm depth) were available at each wireless weather station.

3.5.5. Shallow water table contributions

Contributions to crop ET from a shallow water table were estimated through a modified upward flux (UF_{mod}) equation presented in Yang et al. (2007), where contributions to ET from a shallow WT can be described as

$$UF = \begin{cases} ET, & D \leq Ds \\ ET\left(1 - \frac{Ds - D}{Ds - Dd}\right)^{k \sin\left(\frac{\theta_{90} - \theta r}{\theta s - \theta r} * \frac{\pi}{2}\right)}, & Dd > D > Ds \\ 0, & D \geq Dd \end{cases} \quad (3.7)$$

where ET is evapotranspiration in mm/day; D is the depth to water table in m; Ds represents the threshold at which all ET is sourced entirely from a shallow WT; Dd represents the threshold at which a WT does not contribute to crop ET; k is a parameter related to crop and soil hydraulic properties; θ_{90} is the daily volumetric water content averaged over a 90 cm depth; θ_r is the average residual volumetric water content, unique for each water management practice (Table 3.2); and θ_s is the average saturated volumetric water content, unique for each water management practice (Table 3.2). A visualization of equation 3.7 is presented in Figure 3.9.

The value for Dd was set at 1.9 meters, the maximum depth at which WT readings were taken. It has been shown that WTs lying below 1.9 meters, in silty loam soils, can contribute to crop ET (Franzen, 2007; Brouwer et al., 1985); however, even though water may be contributing from a WT below 1.9 meters, the amount contributing was considered negligible in this study. The value for Ds was set at 0.3 meters. Depths shallower than 0.3 meters have been shown to mimic waterlogged conditions with a corn crop (Skaggs, 1980). However, WTs maintained at

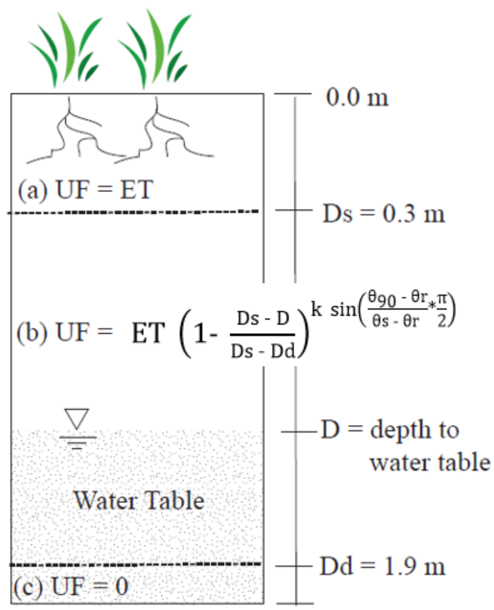


Figure 3.9. A visualization of the upward flux equation 3.7 where ET is evapotranspiration in mm/day; D is the depth to water table in m; Ds represents the threshold at which all ET is sourced entirely from a shallow WT; Dd represents the threshold at which a WT does not contribute to crop ET; k is a parameter related to crop and soil hydraulic properties; θ_{90} is the daily volumetric water content averaged over a 90 cm depth; θ_r is the average residual volumetric water content, unique for each water management practice (Table 3.2); θ_s is the average saturated volumetric water content, unique for each water management practice (Table 3.2)

0.3 meters can still result in an increase in ET compared to a freely drained plot (Tan et al., 2002). A study by Tan et al. (2002) showed, over a clay loam soil and corn crop, WTs maintained at 0.3 meters averaged 87 mm/year more ET versus a freely drained plot (drain tile at 0.6 meter depth). Similarly, for a soybean crop, with a WT maintained at roughly 0.4 meters beneath the ground surface, Cooper et al. (1991) and Madramootoo et al. (1993) saw yield increases of 58% (silt loam) and 15% (sandy loam) compared to free drained plots with the drain tile located around a 1.0 meter depth. Suggesting a WT held at a 0.3 – 0.4 meter depth does not create waterlogged conditions that reduce crop ET below that of a freely drained plot. Therefore, for this study, the value of Ds was set at 0.3 meters beneath the ground surface. In other words, a WT within 0.3 meters of the ground surface for both corn and soybean crops is assumed to contribute entirely to ET with the assumption that there is no reduction in ET due to waterlogged conditions (i.e. the subsurface drain tile would have drained the field before there were ET reductions due to waterlogged soils). This assumption may hold true for this study given the WT did not lie within 0.3 meters of the ground surface for more than 24 hours over both water management practices (SI and CD + SI) and growing seasons (2013, 2014), but should be studied further for alternative crops and WTs which lie within 0.3 meters for longer than 24 hrs.

Modifications to equation 3.7 included a restriction on UF such that the UF is set to zero when daily rainfall (R) and SI amounts exceed daily ET and SSD amounts

$$UF_{mod} = \begin{cases} 0, & R+I>ET+SSD \\ UF, & \text{otherwise} \end{cases} \tag{3.8}$$

Calibration of UF_{mod} involved determining a value for the parameter k (equation 3.7) that would provide similar values of UF_{mod} to estimates of UF through a mass-balance ($UF_{m\text{-}b}$). In-field estimates of $UF_{m\text{-}b}$ were calculated using a mass-balance approach ($UF_{m\text{-}b}$ = ET + SSD + SR – R – SI + ΔS) where all variables were recorded in depth equivalents (mm) and at a daily time step. When selecting a value for the parameter k, trial and error was used to find a value that not only placed data within an appropriate range (fell within a similar range as $UF_{m\text{-}b}$, 0.0-7.5 mm/day) and followed similar dips and peaks as $UF_{m\text{-}b}$, but also ensured seasonal totals were within a reasonable range of $UF_{m\text{-}b}$ ($|UF_{mod} - UF_{m\text{-}b}| < 2.5$ cm). Correlation statistics were not used as the aim was not to replicate estimates of $UF_{m\text{-}b}$, but instead check that estimates of UF_{mod} were reasonable (fell within a similar range as $UF_{m\text{-}b}$). Attempting to replicate estimates of $UF_{m\text{-}b}$ was considered unreasonable due to lack of precision (~2.7 mm) of the soil moisture sensor (Hydra probe) which, even though highly accurate, may not have enough precision to accurately estimate such small amounts of water contributing to daily ET, but instead gives an appropriate range daily contributions, from a shallow WT, can fall in. Through trial and error, k was determined to be 0.5 for a corn crop and 1.0 for a soybean crop. Several other values for k may produce similar results and relating k with a specific crop, region, and soil would be a topic for future study.

3.5.6. Checkbook irrigation scheduling (SWB)

The Checkbook method presented by Lundstrom and Stegman (1988), and adapted for use in spreadsheet form by Steele et al. (2010), uses a soil water mass-balance to determine the soil moisture status of a field and is estimated by

$$\Delta S = S_{i-1} - S_i = ET_i + SR_i + DP_i - R_i - I_i \tag{3.9}$$

where ΔS is the daily change in soil moisture in mm, i is the current day and i-1 the previous day, S_{i-1} and S_i are the previous and current days soil moisture in mm at 11:59 PM, ET_i is evapotranspiration in mm, SR_i is surface runoff in mm, DP_i is deep percolation in mm, R_i is rainfall in mm, and I_i is irrigation in mm. All units are in depth equivalents and represent daily totals. Specifically, the mass-balance used in the Checkbook method assists with estimating the soil moisture status of the field, which in turn helps to estimate the daily SMD. The SMD can be defined as the amount of soil moisture that has been removed below FC or optimal soil moisture status (Lundstrom and Stegman, 1988). In order to report the SMD in terms of percent below FC, knowledge of the available water holding capacity (AWHC) of the soil and the corresponding root zone depth is needed. The AWHC represents the amount of water available to the crop, also referred to as the water that lies between FC and PWP. The AWHC depends on soil type and root zone depth. Tables by Lundstrom and Stegman (1988) provide approximate water storage capacities for different soils. Specifically, soils at the study site are classified as clay loam and silty clay loam, up to a 1.2 m depth, based on the official soil series descriptions of Overly, Colvin, and Bearden soils (NRCS, 2013; USDA-NRCS Soil Survey Division, 2014).

This classification results in an AWHC of 0.18 cm/cm for the soil at the study site (Lundstrom & Stegman, 1988). Hence, the AWHC over the root zone is simply the root zone depth multiplied by 0.18 cm/cm

$$\text{AWHC}=0.18\ \text{RZ} \tag{3.10}$$

where RZ is the daily root zone depth in cm. Daily root zone depth was estimated through a linear growth equation presented in the Spreadsheet Implementation of the Checkbook method by Steele et al. (2010). The linear growth equation, presented by Steele et al. (2010), assumes an initial rooting depth of 10.1 cm which grows linearly until it reaches a maximum rooting depth at the start of the 7th week after crop germination. Maximum rooting depths for corn and soybean were 91 and 70 cm, respectively (Lundstrom and Stegman, 1988). For certain crops, the maximum rooting depth could also be considered to be at the depth of the drain tile, but this would be left to the discretion of the farmer.

Once the AWHC is known, the daily SMD in percent (SMD_p) can be determined by calculating the daily SMD (depth equivalent) and dividing by the daily AWHC

$$\text{SMD}_p=\frac{\text{SMD}_{i-1}+\text{ET}_i+\text{DP}_i+\text{SR}_i-\text{R}_i-\text{I}_i}{\text{AWHC}_i}=\frac{\text{SMD}_i}{\text{AWHC}_i} \tag{3.11}$$

where i is the current day and i-1 the previous day, SMD_i and SMD_{i-1} are the current and previous day's soil moisture deficit in mm, ET_i is evapotranspiration in mm, DP_i is water lost to deep percolation in mm, SR_i is water lost to surface runoff in mm, R_i is daily rainfall in mm, I_i is daily irrigation, and $AWHC_i$ is the daily available water holding capacity over the root zone in mm. It is from this SMD_p value that management decisions can be made regarding the timing of irrigation (Lundstrom and Stegman, 1988). A SMD_p of 100% would mean the soil moisture status of the field is at or below PWP (θ_{PWP}) and a SMD_p of 0% would mean the soil moisture status of the field is at or above FC (θ_{FC}). When the SMD_p is zero, the soil has reached or exceeded FC and the excess water is considered to be lost to surface runoff or deep percolation. The Checkbook method presented by Lundstrom and Stegman (1988) and Steele et al. (2010) does not take into consideration contributions from a shallow WT, SI system, and losses from a SSD system. This can result in inaccurate predictions of the SMD_p.

To improve the accuracy of estimating the daily SMD_p, modifications were made to the Checkbook method presented in equation 3.9, such that additional variables were added to estimate contributions from a shallow WT and SI system, as well as removal through SSD. Inclusion of SSD into the mass-balance equation 3.9, simply involved the addition of daily SSD amounts. Whereas daily SI amounts were not directly included in the mass-balance, but instead, used in conjunction with daily ET and depth to WT measurements, to estimate daily contributions from a shallow WT through upward flux (UF) (equations 3.7, 3.8, and 3.12) (further description provided in following paragraph). Hence, only two components were added to the mass-balance in the original Checkbook method (equation 3.9), SSD and contributions from a shallow WT (UF) (equation 3.12). The other variables (SI and depth to WT) help in estimating daily UF (equations 3.7 and 3.8). The result is

$$\Delta S = S_{i-1} - S_i = ET_i + \mathbf{SSD_i} + SR_i + DP_i - R_i - \mathbf{UF_i} \tag{3.12}$$

where i is the current day and i-1 the previous day, SSD_i represents subsurface drainage, and UF_i represents contributions from a shallow water table through upward flux. A simplified schematic of the water balance variables taken into account with the modified Checkbook method is provided in Figure 3.10.

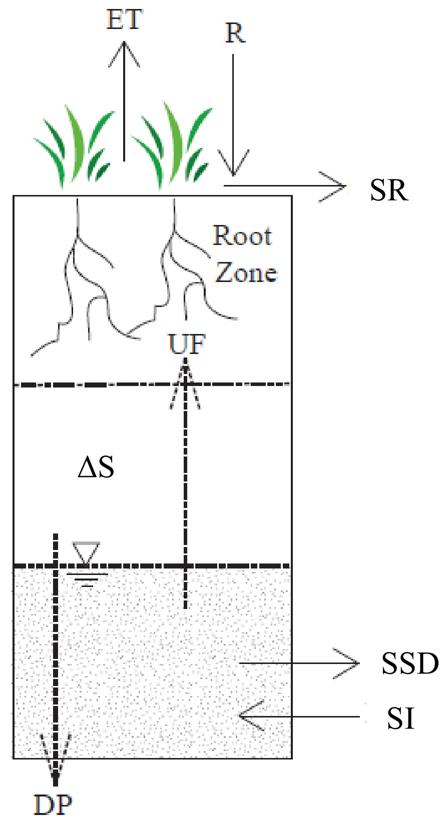


Figure 3.10. Soil water balance schematic. Soil profile is divided into 3 sections (root zone, intervening area between root zone and water table, and depth below the water table). Mass balance variables include evapotranspiration (ET), subsurface drainage (SSD), deep percolation (DP), surface runoff (SR), rainfall (R), subirrigation (SI), and contributions from a shallow WT (UF).

However, even though only two components were added to the mass-balance in the Checkbook method (SSD and UF), estimation of daily UF requires knowledge of daily depth to WT, ET, and soil moisture. For this study, daily ET was estimated through EC for the CD + SI field and the PAR method for the CD field. Missing ET data were substituted with data provided through NDAWN's Crop Water Use calculator which uses reference ET estimated through the J-H method (Jensen & Haise, 1963) along with K_c coefficients developed by Stegman et al. (1977) (NDAWN, 2015). Daily depth to WT was taken as the average WT reading from all six wells within each WMP. Both depth to the WT and ET can be measured or estimated by the farmer through various methods, but the current soil moisture is what needs to be determined through the Checkbook method. Hence, a preliminary estimation of current soil moisture is needed for purposes of estimating current UF. To estimate the current day's soil moisture, a mass-balance is used such that the current day's R, SI, ET, SSD, SR and the previous day's SMD are used to estimate the current SMD as

$$SMD_i = SMD_{i-1} + ET_i + SSD_i + SR_i - R_i - SI_i \tag{3.13}$$

where SMD_i is the current day's soil moisture deficit in mm, SMD_{i-1} is the previous day's soil moisture deficit in mm, ET_i is the current day's evapotranspiration in mm, SSD_i is the current day's sub-surface drainage total in mm, SR_i is the current day's surface runoff as estimated through the SCS curve number method in mm, R_i is the current day's rainfall in mm, and SI_i is the current day's subirrigation total in mm. Once SMD_i has been estimated, it is converted back into a volumetric soil moisture reading through one of four scenarios

$$\theta_V = \begin{cases} \theta_r, & SMD_i \geq D_i\,(\theta_{FC} - \theta_r) \\ \theta_{FC} - \frac{SMD_i}{D_i}, & 0 \leq SMD_i \leq D_i\,(\theta_{FC} - \theta_r) \\ \theta_{FC} - \frac{SMD_i}{D_i}, & SMD_i < 0 \text{ and } |SMD_i| \leq D_i\,(\theta_S - \theta_{FC}) \\ \theta_s, & SMD_i < 0 \text{ and } |SMD_i| > D_i\,(\theta_S - \theta_{FC}) \end{cases} \tag{3.14}$$

where θ_{FC} is the volumetric water content at field capacity (32%), SMD_i is the current day's soil moisture deficit in mm, D_i is the current day's depth to crop root zone mm, θ_s is the saturated volumetric water content (53%), and θ_r is the residual volumetric water content (9%). It is important to note that the estimated volumetric soil moisture does not include additions from a shallow WT (UF) or losses from DP, and therefore does not directly represent daily soil moisture. However, this slight error in soil moisture was assumed to be negligible given its sole purpose is to help with estimation of daily UF and not for direct determination of daily SMD.

An indirect estimation of SMD_i (equation 3.13) was necessary to obtain future soil moisture values without a need for in-field measurements. Once the current daily volumetric soil moisture value is estimated, daily contributions from a shallow WT (UF) can be estimated through equations 3.7 and 3.8.

Thus, the modified Checkbook method (equation 3.12) includes two additional variables in the mass-balance (SSD, UF), but requires three additional daily user inputs (SSD, SI, and depth to WT). In addition, monthly corrections were made to the SMD using in-field estimated SMD over either a 30 or 90 cm depth depending on crop rooting depth. Once the crop rooting depth reached 0.53 m, in-field measured SMD over a 90 cm depth was used for correction, but until then, in-field measured SMD over a 30 cm depth was used. The in-field SMD values were converted to volumetric soil moisture estimates through

$$\mathrm{SMD}_p = \begin{cases} 0.0 & \theta_v > \theta_{FC} \\ 1.0 & \theta_v < \theta_{PWP} \\ \frac{\theta_{FC} - \theta_v}{\theta_{FC} - \theta_{PWP}} & \theta_{PWP} \leq \theta_v \leq \theta_{FC} \end{cases} \tag{3.15}$$

where the SMD_p is in percent (%), θ_{FC} is the field capacity (32%), θ_{PWP} is the permanent wilting point (16%), and θ_V is the volumetric water content over either a 30 or 90 cm depth depending on root zone depth.

4. RESULTS AND DISCUSSION

4.1. ET estimation through PAR

Estimation of EC-ET through the use of PAR and soil moisture data (PAR method) provides a less costly and less labor intensive way of estimating on-site daily ET with relatively the same accuracy as EC-ET. The PAR method compared well with EC-ET, having a coefficient of determination (r^2) of 0.64 for the 2013 growing season (SI field, corn) and 0.45 for the 2014 growing season (SI field, soybean), and a RMSE of 0.88 mm for the 2013 growing season (SI field, corn) and 1.27 mm for the 2014 growing season (SI field, soybean) (Figures 4.1 and 4.2).

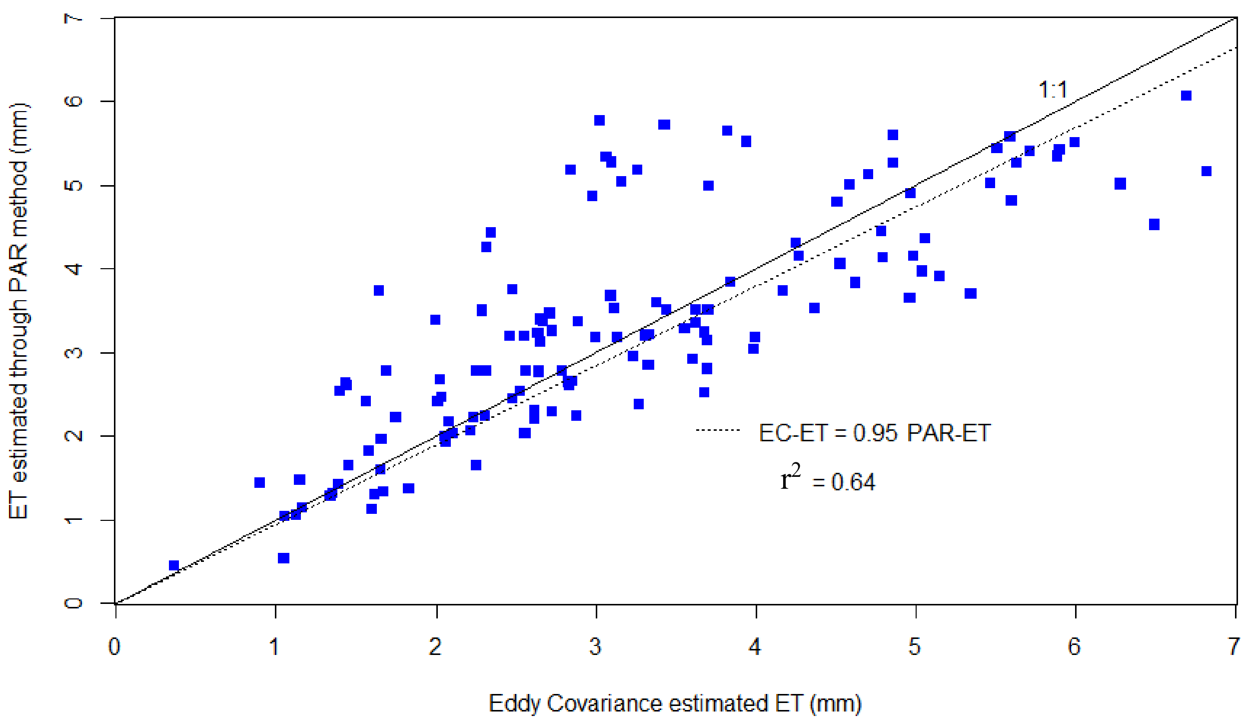


Figure 4.1. Correlation plot of Eddy Covariance estimated evapotranspiration (EC-ET) and evapotranspiration (ET) estimated through the Photosynthetically Active Radiation method (PAR-ET) for the subirrigated corn field in 2013.

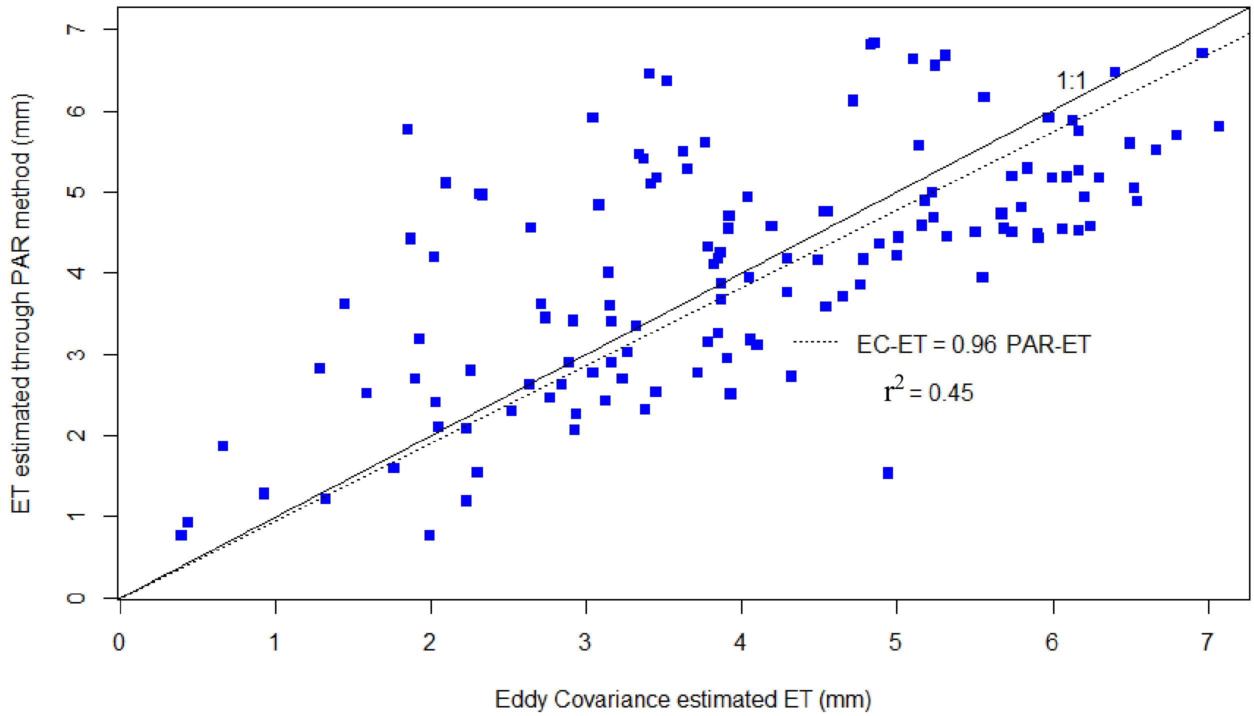


Figure 4.2. Correlation plot of Eddy Covariance estimated evapotranspiration (EC-ET) and evapotranspiration (ET) estimated through the Photosynthetically Active Radiation method (PAR-ET) for the subirrigated soybean field in 2014.

Total seasonal ET estimated through the PAR and EC methods in 2013 was 443.2 and 425.7 mm, respectively and in 2014 it was 521.2 and 538.6 mm, respectively. It is important to note that seasonal totals only take into account days in which both PAR and EC sensors were recording data, hence totals do not represent each day between 5/1 and 9/30, but instead only of those days in which both sensors were recording data.

For both years (2013, 2014) and crops (corn, soybean), the PAR method worked well for predicting ET from mid-June to mid-July and again after mid-August (Figures 4.3 and 4.4).

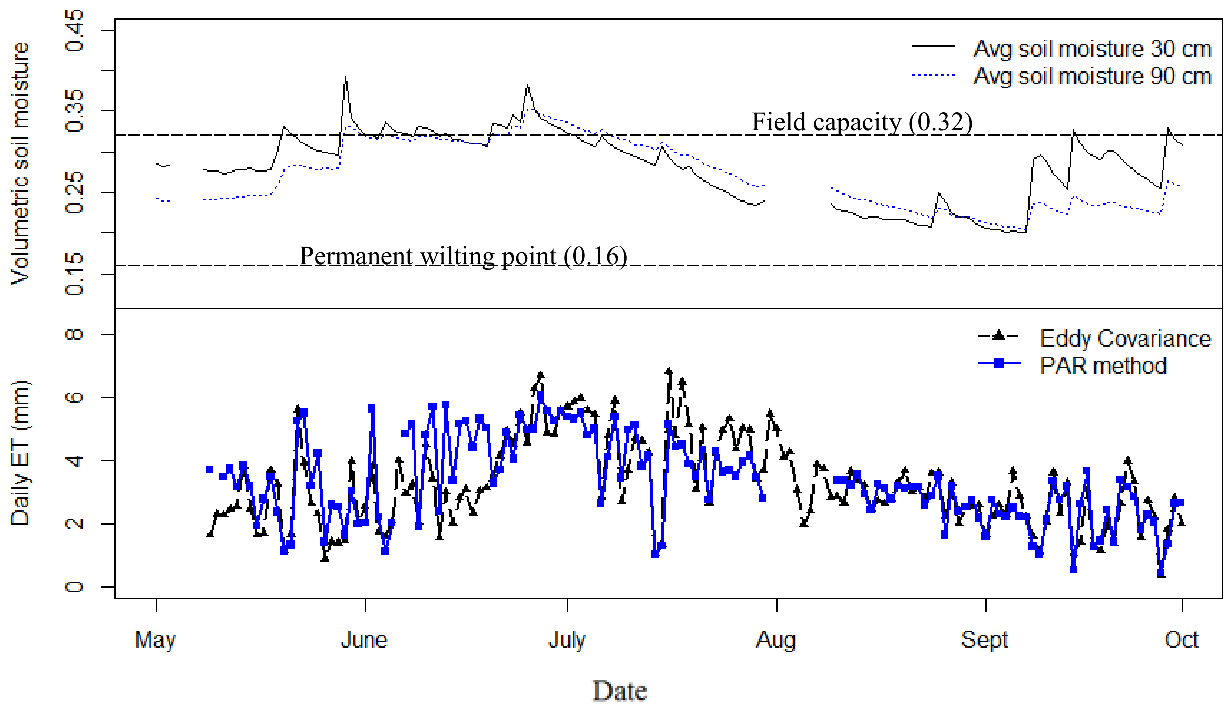


Figure 4.3. Time series of evapotranspiration (ET) estimates using the Photosynthetically Active Radiation (PAR) method as compared to eddy covariance estimates of ET during 2013 for the subirrigated corn site.

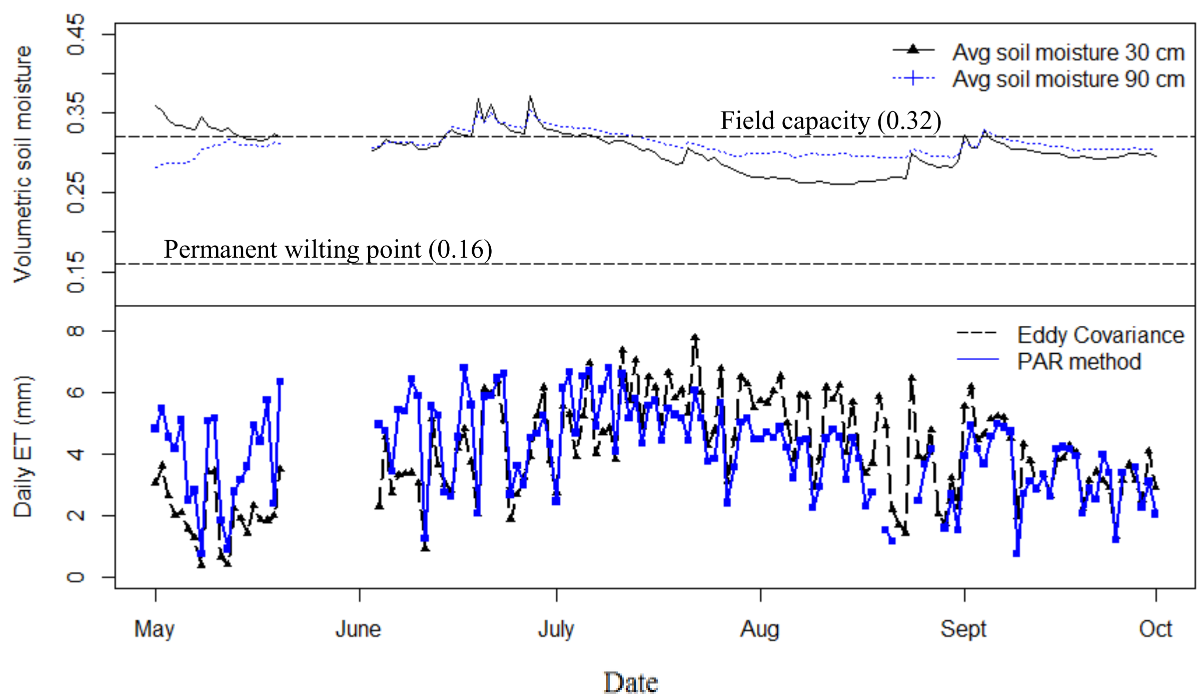


Figure 4.4. Time series of evapotranspiration (ET) estimates using the Photosynthetically Active Radiation (PAR) method as compared to eddy covariance estimates of ET during 2014 for the subirrigated soybean site.

However, the PAR method seems to sporadically over-predict ET at the start of the growing season (before and during crop germination) and seems to under predict ET from late July through early August (a time when crop ET peaks) (Lundstrom & Stegman, 1988; Huffman et al., 2011). The over-prediction of ET at the start of the growing season, and under prediction during the stages prior to pollination/flowering, suggest that consideration of crop growth stage may help with prediction of crop ET by taking into account reduced ET during germination and increased (maximal) ET up to and during pollination/flowering.

4.2. Shallow water table contributions

Contributions from a shallow WT to crop ET using the modified UF method (UF_{mod}) described earlier, gave reasonable results when compared to mass balance estimates of UF (UF_{m-b}) with seasonal totals differing by less than 2.5 cm over each water management practice (CD, CD + SI) and both growing seasons (2013, 2014) (Table 4.1 and Figures 4.5 – 4.8). In addition, UF_{mod} estimates fell within a reasonable range of the UF_{m-b} estimates (0.0 – 7.5 mm/day) while at the same time catching many of the dips and peaks of the UF_{m-b} estimates.

Table 4.1. Shallow water table contributions, through upward flux, using the modified upward flux equation (UF_{mod}) and upward flux estimated through a mass balance (UF_{m-b}) over the 2013 and 2014 growing seasons (5/1 – 9/30) for control drained and control drained + subirrigated water management practices.

		Total seasonal contributions from a shallow water table		
Year	Water management practice	UF_{mod} (cm)	UF_{m-b} (cm)	Number of days in sample
2013	Control drained + subirrigated	17.5	15.0	132
	Control drained	13.5	15.5	115
2014	Control drained + subirrigated	28.2	28.8	136
	Control drained	18.6	17.9	121

However, at varying points over the growing season, when the WT was within 0.4 m of the ground surface and the soil moisture, averaged over a 30 cm depth, was greater than θ_{FC}, $UF_{m\text{-}b}$ estimates recorded zero values. These zero values (signifying no contributions from a shallow WT) were the result of ample water in the soil profile such that, even with subtractions from ET and SSD, soil moisture values were still greater than θ_{FC}, resulting in water losses to deep percolation. For this study, losses to deep percolation varied with the amount of excess water, but future study may involve consideration of a constant rate for deep percolation. These losses, even though in excess of FC, tended to show a net decrease in soil moisture, which resulted in zero contributions from a shallow WT (UF), indicating more water being lost from the soil profile than added through UF. This can be seen in figures 4.5 and 4.6 during late June when $UF_{m\text{-}b}$ estimates dip to or remain at 0.0 mm for a period of time and the WT was within one meter of the ground surface.

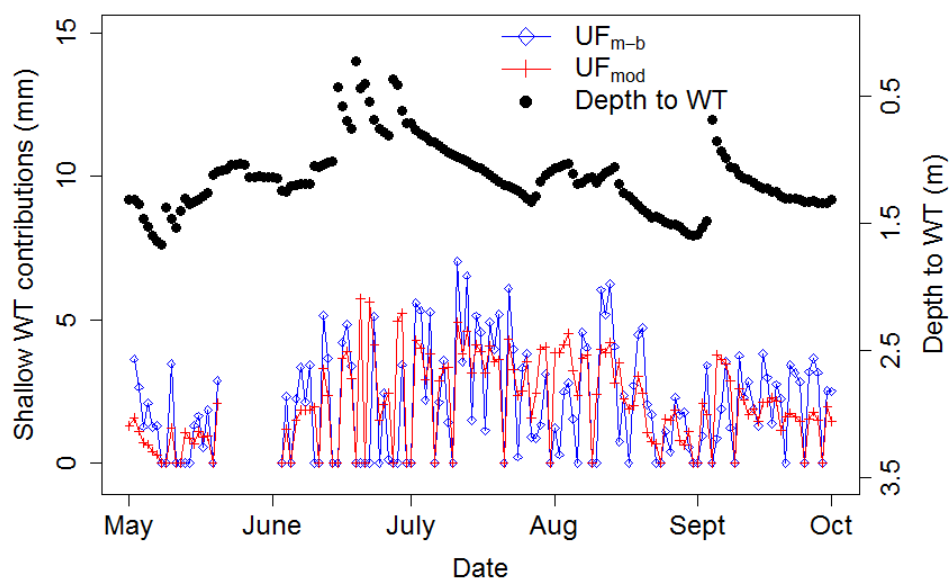


Figure 4.5. Daily shallow water table (WT) contributions to crop evapotranspiration using both the modified upward flux equation (UF_{mod}) and upward flux estimated through a mass balance ($UF_{m\text{-}b}$) methods for the 2014 subirrigated + control drained soybean crop. The WT depth was measured down to a 1.9 meter depth below the ground. Therefore, WT values at a 1.9 meter depth actually represent a WT that is at or below 1.9 meters.

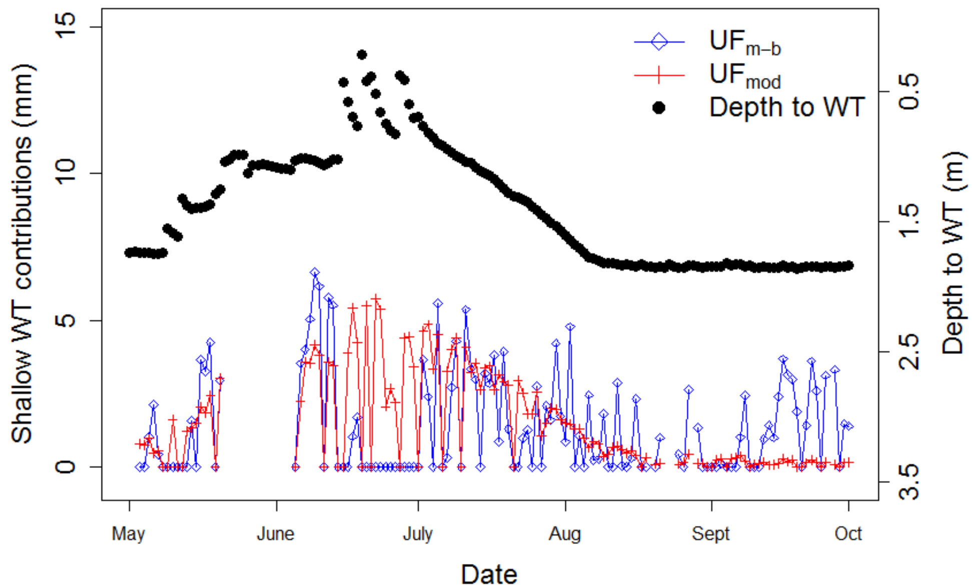


Figure 4.6. Daily shallow water table (WT) contributions to crop evapotranspiration using both the modified upward flux equation (UF_{mod}) and upward flux estimated through a mass balance ($UF_{m\text{-}b}$) methods for the 2014 control drained soybean crop. The WT depth was measured down to a 1.9 meter depth below ground. Therefore, WT values at a 1.9 meter depth actually represent a WT that is at or below 1.9 meters.

Besides the under prediction of UF from the mass-balance method, the modified UF and mass-balance methods seemed to follow similar patterns at the CD + SI site with peaks and dips occurring around the same time over the entire growing season in both 2013 and 2014 (Figures 4.5 and 4.7). On the other hand, the CD field seemed to have more sporadic periods in which UF_{mod} and $UF_{m\text{-}b}$ followed and did not follow similar trends in timing of dips and peaks (Figures 4.6 and 4.8). This may be the result of using the PAR method to estimate ET for the CD site instead of EC-ET, as was done for the CD + SI field.

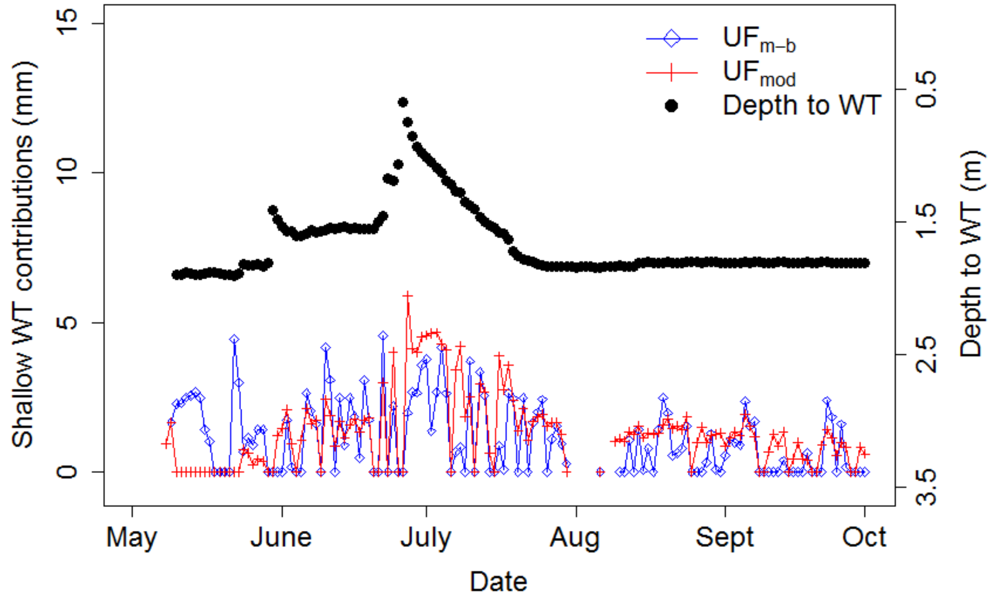


Figure 4.7. Daily shallow water table (WT) contributions to crop evapotranspiration using both the modified upward flux equation (UF_{mod}) and upward flux estimated through a mass balance (UF_{m-b}) methods for the 2013 subirrigated + control drained corn crop. The WT depth was measured down to a 1.9 meter depth below ground. Therefore, WT values at a 1.9 meter depth actually represent a WT that is at or below 1.9 meters.

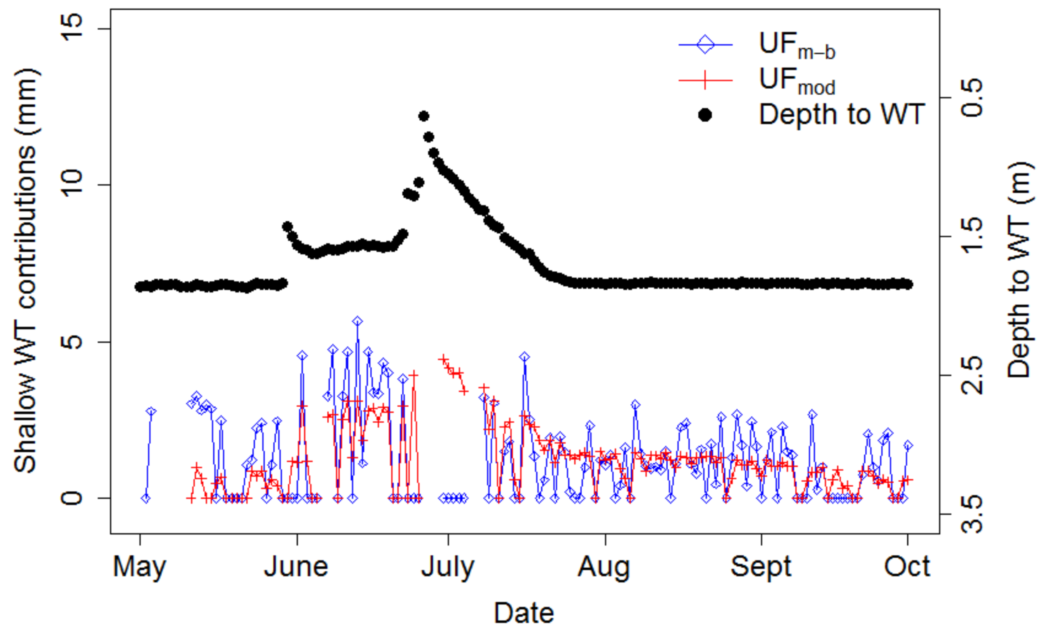


Figure 4.8. Daily shallow water table (WT) contributions to crop evapotranspiration using both the modified upward flux equation (UF_{mod}) and upward flux estimated through a mass balance (UF_{m-b}) methods for the 2013 control drained corn crop. The WT depth was measured down to a 1.9 meter depth below ground. Therefore, WT values at a 1.9 meter depth actually represent a WT that is at or below 1.9 meters.

4.3. Checkbook results

Inclusion of shallow WT contributions through UF in the modified Checkbook method (equation 3.12) reduced the tendency for over-estimation of SMD_p. For purposes of comparison of the Checkbook method with and without inclusion of contributions from UF, the original Checkbook method has the same mass balance as noted in equation 3.9, but with the addition of SSD. In other words, the original Checkbook method has the same mass balance as noted in equation 3.12, but without consideration of UF. Whereas the modified Checkbook method includes both SSD and UF in the water balance (equation 3.12). Further description of the modified Checkbook method is provided in the Appendix.

For the 2013 corn crop, modified Checkbook estimates of SMD_p ($SMD_{SSD,UF}$) were similar to in-field estimates of SMD_p, with a correlation of 0.93 and 0.89 for CD and CD + SI sites, respectively. Similarly, estimates of SMD_p by the original Checkbook method (SMD_{SSD}) related well with in-field estimates having slightly higher correlations of 0.96 and 0.92 for CD and CD + SI sites, respectively. Even though the correlations were relatively high for both $SMD_{SSD,UF}$ and SMD_{SSD}, $SMD_{SSD,UF}$ tended to under predict in-field estimates of SMD_p over the month of July for both CD and CD + SI fields, suggesting contributions from a shallow WT (UF) were minimal, for a corn crop, once the WT fell below a 1.5 meter depth. This may be attributed to the WT remaining below 1.5 meters for 131 out of the 154 days at the CD field and 119 out of the 154 days at the CD + SI field over the 2013 growing season (5/1 – 9/30). In addition, $SMD_{SSD,UF}$ and SMD_{SSD} were much higher than the in-field estimates of SMD_p during the middle of May. This is largely attributed to $SMD_{SSD,UF}$ and SMD_{SSD} only being considered over the crop root zone, which is very small at the start of the season. The small root zone also results in a smaller AWHC value (equation 3.10). Therefore, a relatively small SMD value (depth equivalent) could seem quite large when compared to the AWHC over a small root zone (equation 3.11). Hence, when $SMD_{SSD,UF}$ and SMD_{SSD} are compared to in-field SMD over 30 and 90 cm, they seem relatively large given they are considered over such a small depth. Specifically, during the middle of May the estimated root zone depth for corn was between 10 – 22 cm, resulting in much lower $SMD_{SSD,UF}$ and SMD_{SSD} values as compared to the in-field 30 cm SMD. Overall, both $SMD_{SSD,UF}$ and SMD_{SSD} compared well with in-field estimates of SMD for the 2013 growing season with a corn crop (Figures 4.9 and 4.10)

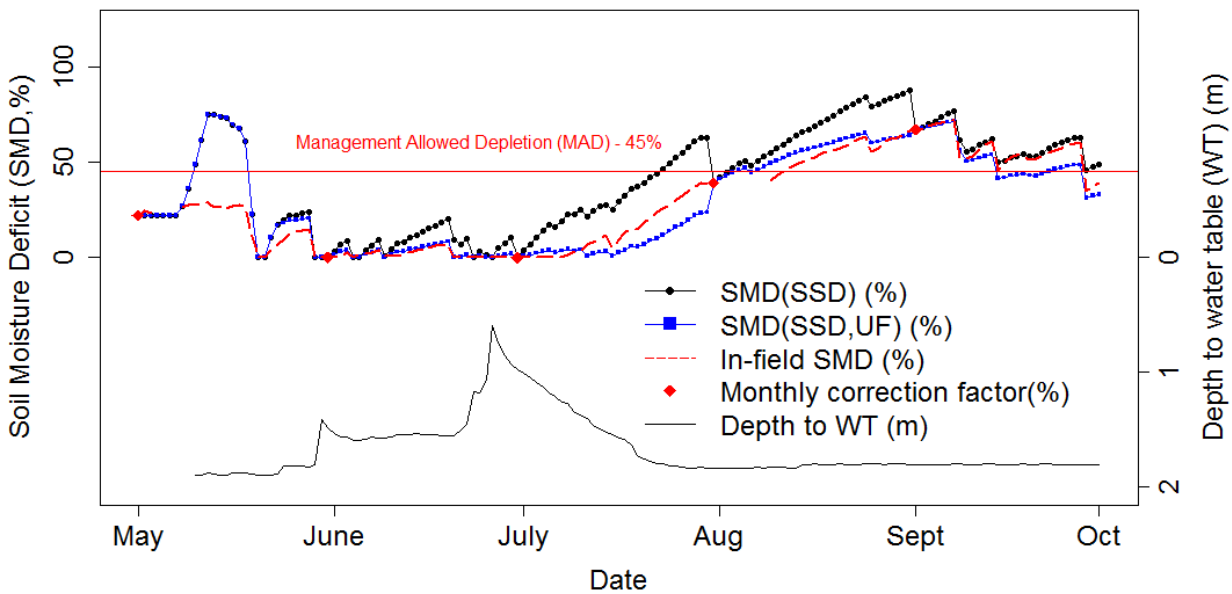


Figure 4.9. Soil moisture deficit (SMD) values for the original Checkbook method with subsurface drainage (SMD_{SSD}) and modified Checkbook method with subsurface drainage and contributions from upward flux ($SMD_{SSD,UF}$), in-field SMD averaged over 30 cm, and in-field SMD averaged over 90 cm for the control drained + subirrigated site with a corn crop in 2013. The water table depth was measured up to a 1.9 meter depth. Therefore, water table values at a 1.9 meter depth actually represent a water table that is at or below 1.9 meter

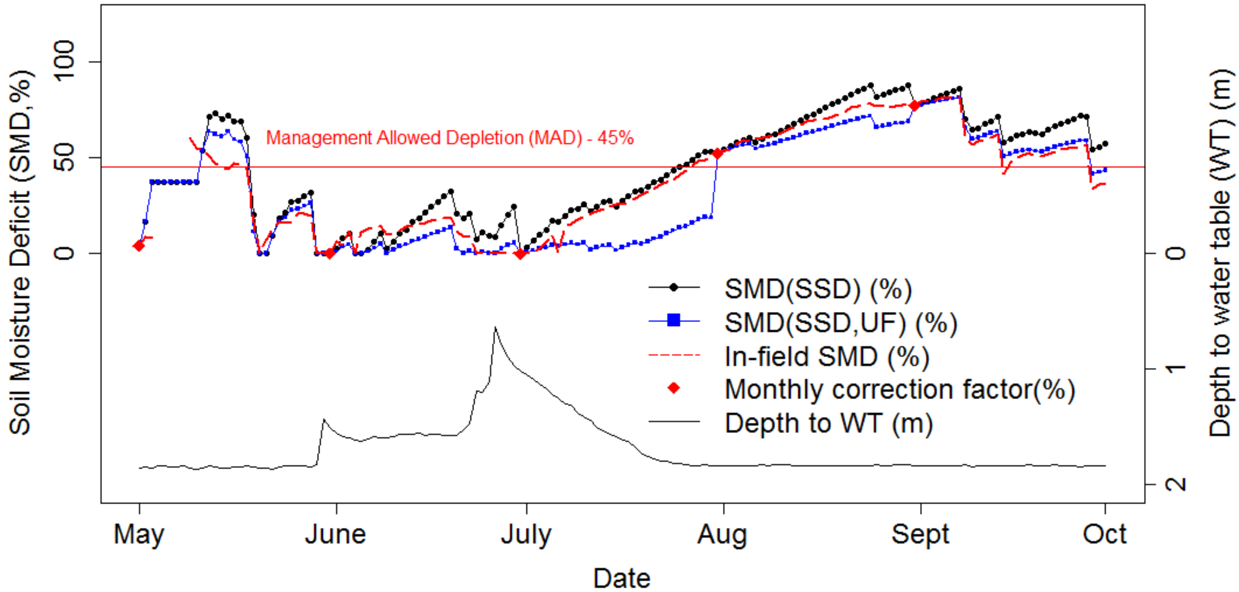


Figure 4.10. Soil moisture deficit (SMD) for the original Checkbook method with subsurface drainage (SMD_{SSD}) and modified Checkbook method with subsurface drainage and contributions from upward flux ($SMD_{SSD,UF}$), in-field SMD averaged over 30 cm, and in-field SMD averaged over 90 cm for the control drained site with a corn crop in 2013. The water table depth was measured up to a 1.9 meter depth. Therefore, water table values at a 1.9 meter depth actually represent a water table that is at or below 1.9 meters.

For the 2014 soybean crop, contributions from a shallow WT (UF) significantly reduced daily $SMD_{SSD,UF}$ compared to SMD_{SSD}, and resulted in a closer estimate of in-field SMD_p with correlations of 0.70 and 0.75 for CD and CD + SI fields compared to SMD_{SSD} correlations of 0.24 and 0.67 for CD and CD + SI fields. This is in large part attributed to the WT remaining within 1.5 meters of the ground surface 143 out of 154 days for the CD + SI field and 79 out of 154 days for the CD field over the 2014 growing season (5/1-9/30) (Figures 4.11 and 4.12).

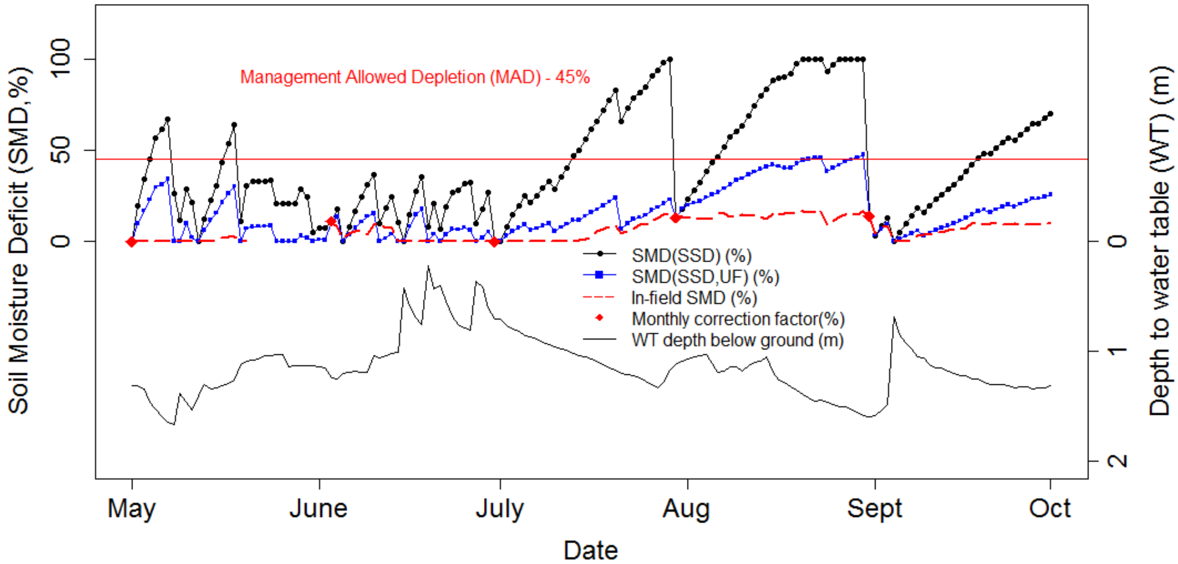


Figure 4.11. Soil moisture deficit (SMD) values for the original Checkbook method with subsurface drainage (SMD_{SSD}) and modified Checkbook method with subsurface drainage and contributions from upward flux ($SMD_{SSD,UF}$), in-field SMD averaged over 30 cm, and in-field SMD averaged over 90 cm for the control drained + subirrigated site with a soybean crop in 2014. The water table depth was measured up to a 1.9 meter depth. Therefore, water table values at a 1.9 meter depth actually represent a water table that is at or below 1.9 meters.

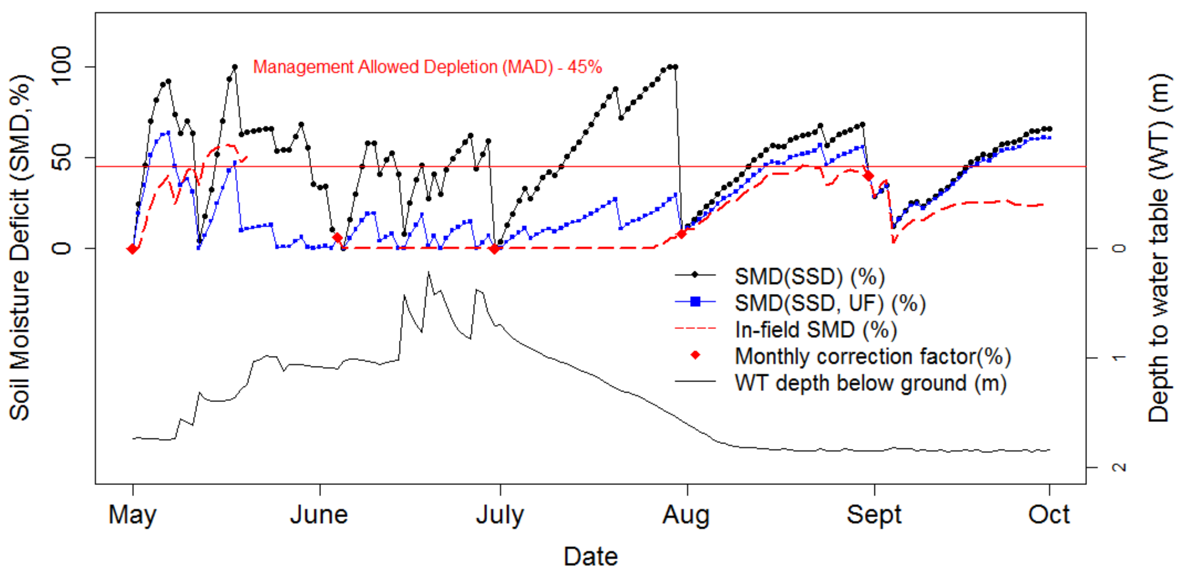


Figure 4.12. Soil moisture deficit (SMD) values for the original Checkbook method with subsurface drainage (SMD_{SSD}) and modified Checkbook method with subsurface drainage and contributions from upward flux ($SMD_{SSD,UF}$), in-field SMD averaged over 30 cm, and in-field SMD averaged over 90 cm for the control drained site with a soybean crop in 2014. The water table depth was measured up to a 1.9 meter depth. Therefore, water table values at a 1.9 meter depth actually represent a water table that is at or below 1.9 meters.

Provided the MAD was set at a 45% SMD_p, SMD_{SSD} estimates had a tendency to surpass MAD more often than both $SMD_{SSD,UF}$ and in-field estimates of SMD, with significant differences in 2014 (Table 4.2). Supporting the use of the modified Checkbook method, over the original, for estimation of in-field SMD_p, as inaccurate estimates of SMD_p above the MAD could potentially lead to over-irrigation.

Table 4.2. Number of days where the soil moisture deficit (SMD) surpassed the management allowed depletion (MAD) for the original Checkbook method (SMD_{SSD}), modified Checkbook method ($SMD_{SSD,UF}$), and in-field estimates of SMD for control drained and control drained + subirrigated field sites. Days for which there was no in-field SMD data available were not included in the analysis.

Number of days where SMD exceeded MAD (45%)				
	2013		2014	
	Control drained	Control drained + subirrigated	Control drained	Control drained + subirrigated
SMD_{SSD}	76	70	79	61
$SMD_{SSD,UF}$	67	51	36	5
SMD (in-field)	70	48	10	0

5. FUTURE WORK

In this study, EC-ET was considered the standard and measured in-field. The EC-ET was used to calibrate and validate ET estimated through the PAR method. Further study may look at comparisons of EC-ET and PAR-ET with ET estimates provided through the Checkbook tables by Lundstrom and Stegman (1988). However, for this paper, in-field estimated EC-ET was used for comparison to estimate, as accurately as possible, the water balance as EC-ET is considered to represent in-field conditions more accurately than ET estimates provided through the Checkbook tables.

In addition, this study did not consider setting a threshold for daily SSD and SI amounts. The daily drainage capacity of the subsurface system in this study was 7.14 mm/day (largest measured daily drainage was 5.08 mm/day). Assuming the SI setup could irrigate at this same rate (7.14 mm/day), the maximum daily irrigation fell below this value at 5.84 mm/day. Hence, for this study thresholds for SSD and SI would not have made a difference. However for other studies knowledge of system specific daily SSD and SI thresholds could help farmers better understand how readily they can either drain or irrigate their fields.

The methods presented in this study also required the continuous monitoring and recording of the WT to predict future soil moisture deficit values. Daily WT monitoring allowed for the daily estimation of shallow WT contributions to ET. Further studies could look at establishing a relationship between WT drop and water yield (specific yield) and its relation to crop ET. In addition, monitoring of the WT can be tedious and knowledge of soils, crop type/stage, and future precipitation could allow for prediction of future WT depths. Further investigation into alternative methods/equations to predict WT depth is an area left for future study.

Lastly, reductions to ET, due to waterlogged conditions, were not considered in this study. During the study, it was assumed the field drained to FC within 24 hrs and that any crop stress caused by excess water was insignificant. However, this may not hold true for every field and future work may look at reducing crop ET as the WT approaches the ground surface.

6. CONCLUSIONS

Estimation of evapotranspiration (ET) using photosynthetically active radiation and soil moisture (averaged over a 30 cm depth) provided an alternative method (Photosynthetically Active Radiation, PAR, method) for estimating in-field ET at a lower cost and involving less equipment. The PAR method produced reasonable estimates of daily ET ($r^2 = 0.64$, 2013; $r^2 = 0.45$, 2014), with a tendency to over predict ET during crop germination stage and under predict ET as the crop approached pollination (corn)/flowering (soybean), suggesting the consideration of crop growth stage to help adjust daily ET values based on crop development. Both eddy covariance ET and ET estimated through the PAR method provided reasonable results when used to estimate daily contributions from a shallow water table (WT) through upward flux (UF), with calculations using eddy covariance ET comparing closer to mass-balance estimates of UF than calculations using the PAR method.

Incorporation of UF and SSD into the Checkbook method led to similar, if not closer, estimates of in-field soil moisture deficit (SMD) compared to using the Checkbook method without consideration of UF. Significant improvements were seen when the WT was within 1.5 m of the ground surface for a majority of the growing season (5/1 - 9/30). Over the 2014 growing season (154 days) the WT was within 1.5 m of the ground surface 79 days for the CD site and 143 days for the CD + SI site, resulting in closer estimates of in-field SMD through the modified Checkbook method ($SMD_{SSD,UF}$) (R = 0.70, CD; R = 0.75, CD +SI), with consideration of UF and SSD, compared to the Checkbook method without consideration of UF (SMD_{SSD}) (R = 0.24, CD; R = 0.67, CD+SI). This study therefore suggests the use of the modified Checkbook method with consideration of UF and SSD, would be more beneficial to farmers dealing with a shallow WT, either naturally occurring or induced through SI. However, in 2013 the WT was within 1.5 m of the ground surface less than 23 days for the CD site and 35 days for the CD + SI site, resulting in similar estimates of in-field SMD by $SMD_{SSD,UF}$ and SMD_{SSD}, with correlations (R) greater than 0.88 for both CD and CD + SI sites. Thus, the modified Checkbook method seemed to provide similar, if not better estimates, of in-field SMD. By taking into consideration contributions from UF and SSD into the Checkbook method, a farmer can better estimate the time and amount needed for irrigation and drainage by looking at 'what –if' scenarios, which in turn saves water, costs of pumping, and increases crop security.

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APPENDIX

For this study, the spreadsheet version of the Checkbook Method by Steele et al. (2010), was modified to account for subsurface contributions and subtractions to/from the water balance. The spreadsheet can be adjusted to work with both Standard and English units. For the following example, English units were used. A detailed description of the original spreadsheet is provided in the paper by Steele et al. (2010). To avoid redundancy, only modifications to this spreadsheet will be discussed.

General modifications to the original spreadsheet include substitution of effective irrigation (I) with contributions from a shallow WT (either naturally occurring or induced through SI) through UF (column I), and inclusion of SSD in the water balance (column V) (Figure 13). Specifically, estimation of contributions from a shallow WT through UF, requires daily measurement of subirrigation (column W) and depth to WT (column X) (Figure 13).

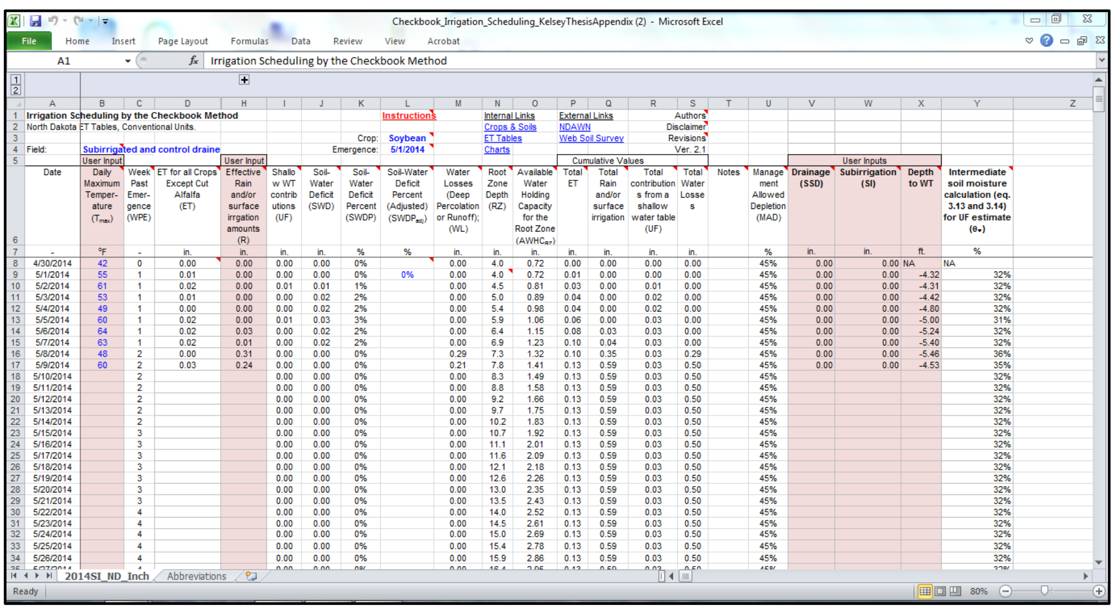

Figure A1. Spreadsheet layout of the modified Checkbook Method for water balance irrigation and drainage scheduling. Additional columns V (subsurface drainage), W (subirrigation), X (depth to water table), and Y (intermediate soil moisture calculation), along with the modified column I (shallow water table contributions through upward flux), help to better estimate the soil moisture deficit when managing a subsurface system.

In the original spreadsheet by Steele et al. (2010), a crop can be selected and a lookup table of daily ET estimates provided by Lundstrom and Stegman (1988) for the specific crop are populated in the ET column (column D). However, for this study, in-field estimated ET (through EC and PAR methods) was available and considered to be more accurate than estimates from tables by Lundstrom and Stegman (1988). Therefore, ET estimated through EC and PAR methods replaced the original ET estimates calculated through the spreadsheet, but for other studies, the original lookup table for daily ET estimates by Lundstrom and Stegman (1988), remains in the updated spreadsheet. Estimates of shallow WT contributions to ET through UF require daily measurements of depth to WT and SI amounts (columns W and X). The spreadsheet uses daily WT depth and SI amounts to estimate contributions to ET through UF, via equations mentioned in the sections 'Shallow water table contributions' and 'Checkbook irrigation scheduling (SWB)' (equations 3.7, 3.8, 3.13, and 3.14). First, equations 3.13 and 3.14 were used to estimate the intermediate volumetric soil moisture content (column Y in Figure 13) and then equations 3.7 and 3.8 were used to estimate shallow WT contributions through UF (column I in Figure 13). The additional and modified columns through the spreadsheet implementation of the Checkbook method represent modifications to the original soil water balance (equation 3.9) form the soil water balance in equation 3.12.